EVALUATION OF DEEP TILLAGE IN COHESIVE SOILS OF QUEENSLAND, AUSTRALIA

A thesis submitted by

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B.Sc., M.Sc.

For the award of

Doctor of Philosophy

2021

ABSTRACT

With the rapid global trend towards mechanized, continuous and dense cropping systems that provide agricultural efficiency to meet consumer demand, soil compaction has become a recognized problem. Soil compaction under modern machines has had immense impact on productive land's physical, chemical and biological properties, including soil-water storage capacity, fertiliser use efficiency, and plant root architecture. As a result, farms are experiencing substantially reduced crop yields and economic returns. The percentage of soil compaction increases with increased soil clay fraction. Numerous investigations have been conducted to evaluate the technical, economic and soil-crop efficiency of compaction mitigation strategies, but deep tillage has not received sufficient consideration, particularly in relation to high clay content soils.

This study was conducted to technically and economically evaluate a range of deep ripping systems, and study the effect of tillage on soil and crop grown on cohesive soils. A series of field experiments were conducted to parametrise a soil tillage force prediction model, previously developed by Godwin and O'Dogherty (2007) and the Agricultural Productions Systems sIMulator (APSIM) developed by the Agricultural Production Systems Research Unit in Australia (Holzworth et al., 2014; Keating et al., 2003). The behaviour of soil physical properties, power requirements of ripping operations and cost, and agronomic and economic performance of sorghum and wheat were assessed at the University of Southern Queensland's research ground in Toowoomba, Queensland (Australia) over two consecutive seasons (2015-16 and 2016-17). The work was conducted by replicating the soil conditions commonly found in non-controlled or 'random' traffic farming systems, referred to as RTF. Sorghum was also grown at a commercial farm located in Evanslea near Toowoomba, under controlled traffic (CTF) conditions (a farm system based on a permanent lanes for machinery traffic) during the 2018 summer crop season.

The soil types at the two sites are Red Ferrosol (69.1% clay, 10.0% silt, and 20.9% sand) and Black Vertosol (64.8% clay, 23.4% silt, and 11.8% sand). Three levels of deep ripping depth, namely, Deep Ripping 1 (D1= 0-0.3 m), Deep Ripping 2 (D2= 0-0.6 m), and Control (C= no ripping) were applied using a Barrow single tine ripper at the Ag plot site - USQ, and a Tilco eight-tine ripper was used at the Evanslea site. The

tillage operations were performed at 2.7 km/h. A predetermined optimum N fertiliser rate was applied after sorghum and wheat sowing at the Ag plot site. The field experiments were conducted according to the randomized complete block design (RCBD). The Statistical Package for Social Scientists (SPSS) software was utilized to analyse the significance of the differences between the variables at the probability level of 5% as the least significant difference (LSD).

The statistical analysis results showed that the D2 treatment significantly reduced soil bulk density and soil strength by up to 5% and 24% for Red Ferrosol soil, and by up to 6% and 40% for Black Vertosol soil respectively, and increased water content compared with the D1 and C treatments. Overall results showed that D2 was superior in ameliorating the properties of both soils. In both soils, energy requirement results showed that tillage draft force and tractor power requirements were dependent on tillage depth, but for both tillage treatments, energy consumption was slightly lower for the CTF system (Evanslea site) than the RTF system at Ag plot site.

Crop performance results showed that at the Ag plot site, the grain and biomass yields were highest by up to 19% for sorghum and by up to 30% for wheat when the D2 treatment was applied, compared to the D1 and C treated crop yield components. Also, the grain and biomass yields were highest for fertilised soil by up to 10% for sorghum and by up to 16% and 25% for wheat respectively, in comparison with the non-fertilised treatments soils yield. Fertilising of D2 treated soil produced the highest significant yield of sorghum grain (5360 kg/ha), biomass (13269 kg/ha), wheat grain (2419 kg/ha), and biomass (5960 kg/ha) compared to the yield of the other treatment interactions. However, at Evanslea site, the D1 treatment showed significantly higher yield and yield components for sorghum compared with C practice (by up to 17% higher yield), and no differences were observed for treatment D2.

Economically, the D1 treatment required the lowest total operational cost at both sites, which was estimated at AUD125/ha and AUD25.8/ha at the Ag plot and Evanslea sites, respectively. These results compare to AUD139.3/ha (Ag plot) and AUD30.8/ha (Evanslea) for the D2 ripping system. With regard to economic returns, at the Ag plot site, D2 yielded the highest sorghum gross benefit (AUD1422/ha) and net benefit (AUD1122/ha), wheat gross benefit (AUD590/ha) and net benefit (AUD482.3/ha), 2017 season gross benefit (AUD 2011.7/ha) and 2017 season net benefit (AUD

1604.7/ha), compared to D1 and C soil benefits. The economic fertiliser application at this site achieved the highest gross benefit for sorghum (AUD1384.2/ha), wheat (AUD555.6/ha), and 2017 season (AUD1939.8/ha) respectively, in comparison with the non-fertilised soils' total return. Also, fertilised D2 treated soil resulted in the highest sorghum gross benefit (AUD1512.9/ha) and net benefit (AUD1170.3/ha), wheat gross benefit (AUD633.7/ha) and net benefit (AUD492.4/ha), 2017 season gross benefit (AUD2146.6/ha), and net benefit (AUD1662.7/ha) compared to other interactions' benefits. At the Evanslea site, D1 significantly increased sorghum gross benefit and net benefit by up to 17% (AUD2277.9/ha) and by up to 20% (AUD1825.5/ha), respectively compared to C benefits, and no differences were observed with treatment D2.

The average of APSIM derived results for the long-term (1980-2017) at the Ag plot site showed that the D2 treatment reported consistently higher grain sorghum (4192 kg/ha), biomass (11454 kg/ha), wheat grain (3783 kg/ha), and biomass (10623kg/ha), compared to the D1 and C treatments' yields under the same long-term conditions. However, at the Evanslea site, for long-term (1980-2018), APSIM simulation showed that D1 treatment increased the yield of sorghum grain and biomass significantly by up to 10% (5823 kg/ha) and 11% (12171 kg/ha), respectively compared to C treatment's production, but these increases were found not significant with the D2 yields' components. APSIM model simulation of field experiment conditions during 2017 season at the Ag plot site showed that the D2 treatment also had the highest significant yield of sorghum grain (5284 kg/ha), biomass (12488 kg/ha), wheat grain (2341 kg/ha) and biomass (6081 kg/ha) compared to the C and D1 crop yields. Similarly, APSIM model simulation of field experiment circumstances during the 2018 season at the Evanslea site showed that the D1 treatment produced the highest yield of sorghum grain (7129 kg/ha), biomass (13364 kg/ha) yields, compared to the C and D1 crop yields.

Overall, both the long and short-term model outputs were in good agreement with experimental data, suggesting beneficial effects of deep tillage in improving cereal crops' productivity in this region. Moreover, in comparison with the study findings, the model prediction error rate was ±7, which indicates that the developed model approach is valid and calibrated during this study.

Results derived from the G&O soil tillage mechanics model under the Ag plot and Evanslea soil conditions showed that the required tractive force increases with the increasing operation working depth. Furthermore, the D1 was superior, requiring the lowest draft force at Ag plot (7.48 kN) and Evanslea (19.65 kN) soils, compared to the D2 required forces which were 43.28 kN and 41.41kN at both sites, respectively. In general, the model values were in line with the experiments' draft forces and when compared with the study readings, the model prediction error rate was ±8, which indicates that it is also valid and calibrated during this study.

Finally, the study provides conclusions and recommendations that contribute to crop production improvement in the face of recurrent and increasing challenges, as well as emphasizing the necessity of correct management and cultivation of economically important crops after the application of deep ripping to produce accurate results that serve decision-making in the agricultural sector.

THESIS CERTIFICATE PAGE

This Thesis is entirely the work of Kasem Mosa M. AL-Halfi except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Professor John McLean Bennett, *CPSS*

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Student and supervisor's signatures of endorsement are held at the University.

ACKNOWLEDGMENTS

At the end of this research adventure and thesis writing, I have to thank those who were helpful and supportive to me during the study period.

First, I would like to profess my deepest gratitude to my supervisors, Prof. John McLean Bennett, Assoc. Prof. Troy Jensen, and Dr. Diogenes L. Antille, for the advice, guidance, mentorship, persistence and hard work in shaping my professional growth. Their help and support during the research years went far beyond the academic and technical aspects of this project. *Thank you!*

This research was made possible through financial assistance from the Iraqi Government's Ministry of Higher Education and Scientific Research (MoHESR), Australian Commonwealth Government contribution through the Research Training Program (RTP) and the University of Southern Queensland (USQ). *Thank you!*

I am grateful to my late mother every day for what she gave me and what that means for my life today. Yes, I lost her during this study but her loss isn't painful because I feel that she is with me every day, and that make me happy. *Thank you Mum*!

Special gratitude goes to my wife, sons, brother, and sister who have been a continual source of inspiration, support and encouragement. Without them all I may not have successfully made it to the end of this study. *Thank you!*

I also wish to acknowledge the support and assistance provided by Mr Andrew Ruhle who devoted part of his field and farm machinery to conduct the research investigations. He is a very respectable person and deserves to be thanked and appreciated. *Thank you!*

I would also like to commend the support and assistance provided by Prof. R.J. Godwin who was always in touch during the model checking period. His valuable remarks had a great impact on the study's progress. For his efforts, many thanks and appreciation. *Thank you!*

I also wish to acknowledge the editorial support provided by the English editor, Ms Sandra Cochrane, and my supervisory team which reviewed the earlier versions of this thesis for grammar and scientific research context. *Thank you!*

Many thanks must go to Dr. Mahmood Hussein, Dr. Mohammed AL-Shatib, Dr. Adnan Luhaib, Dr. Mr Mohammed Haraz, Dr. Aram Ali, Dr. Stirling Roberton, Dr. Sombat Khawprateep, and Dr. Kojo Atta Aikins for their significant contribution and ongoing assistance at all stages of the experimental work. I also wish to thank Dr. Buddhi Wahalathantri, Dr. Afshin Ghahramani, Dr. Mac Kirby, and Mrs Jo Owens for their invaluable help with the modelling work. Technical assistance from Dr. Steven Rees, Dr. Alla Marchuk, Mrs Piumika Ariyadasa, Mr. Gary Sandell, Mr. Chris Galligan, Mr. Bruen Smith, Mr. Daniel Eising, Mr. Brian Aston, Mr. Oliver Kinder, Mr. Mohan Trada, and Mr. Jason Sheedy (USQ, Toowoomba), Mr. Andrew Short (Pacific seeds, Toowoomba), Mr. Luke Hogan and Mr. Stephen Ellis (Rimik Pty Ltd) has been greatly appreciated.

Thank you!

CONTRIBUTIONS TO THEORY AND PRACTICE OF THIS RESEARCH

This project can be described as a comprehensive study with objectives addressing many vital issues related to the sustainability of soil quality, crop productivity, machinery units and farm economics, as well as the management of farm resources. Selecting deep ripping as a policy for reducing soil compaction, especially clay soils, is challenging, but the gains could benefit the agricultural sector substantially if carefully implemented. The main contributions to theory and practice arising from this research are summarised below:

- This research provides findings regarding soil physical behaviour and crop yield response to deep tillage systems in clay soils affected by agricultural machinery traffic under CTF and RTF systems
- This research gives a detailed analysis of the yield-to-best fertiliser rate response in RTF compacted and ripped soil conditions. Thus, the outcomes enabled study to determine the most efficient combination for this system
- Of importance, the determination of best practice fertiliser rates is difficult where a soil is already suffering from compaction. Modifying the soil structure and improving its physical properties may later reduce the amount of applied fertiliser, increase its efficiency, and make it a valuable and economically feasible process. This study provides an assessment of fertiliser management in a soil system largely alleviated from the soil compaction constraint
- Since most growers tend to adopt shallow practices to increase crop productivity and avoid deep tillage due to the high cost (especially in high clay content soils), this research justifies investigation into very deep tillage. The work targeted the adoption costs, crop/s yield and farm benefits for two different machine traffic systems
- This study may be a pioneer in its employment the developed approach of the Agricultural Production Systems Simulator (APSIM) model in simulating long- and short-term deep ripping system effects on crop yield components of two clayey soils. Thus, the model was effective and may be used to assess further deep tillage studies as well as contribute to farm decision making

- Since it had not previously been used or investigated in very high clay content soils, e.g. Vertosols (Bennett, 2016), this study also investigated the validity of the Godwin and O'Dogherty (G&O) model's prediction of required draft force in Queensland high clay soils and in the deep tillage practices. Therefore, model validity investigation is considered one of the study's novelties
- Based on the field experiments and model outputs, this research has the ability to recommend guidelines that will increase farm efficiency and productivity, and enhance farm management's ability to formulate future policies.

LIST OF RELATED PUBLICATIONS

Proposed articles to publish under writing

AL-Halfi, K. M. M, Bennett, J. M, Jensen, T, Antille, D. L, 'Deep tillage technology improves optimum urea rate efficiency of wheat (Spitfire) yields in high clay content soil (Red Ferrosol) - Southern Queensland: Field investigations and modelling'.

AL-Halfi, K. M. M, Bennett, J. M, Jensen, T, Antille, D. L, 'Deep tillage technology improves sorghum (Elite Mr Buster) yields' components in high clay content soil (Black Vertosol) - Southern Queensland under CTF system: Field investigations and modelling'.

CONFERENCE PROCEEDINGS

Al-Halfi, K. M. M., Bennet, J. M., & Jensen, T. (2017). Investigating the validity of the Godwin & O'Dogherty single tine model for a Red Ferrosol clay soil - Queensland. *In Proceedings of the 1st MoHESR and HCED Iraqi Scholars Conference in Australasia 2017* (pp. 368-374). Swinburne University of Technology, Melbourne, Australia, 5-6 December. https://researchbank.swinburne.edu.au/items/b083d58b-327d-464f-906e-57530405c7c5/1/

Al-Halfi, K. M. M., Hussien, A. M., Bennet, J. M., & Jensen, T., Antille, D. L., (2020). Deep tillage technology improves optimum urea rate application efficiency on sorghum (Elite Mr Buster) yields in high clay content soil (Red Ferrosol) - Southern Queensland: Field investigations and modelling. *In Proceedings of the First International Virtual Conference on Agricultural Sciences*. College of Agricultural Engineering Sciences, University of Baghdad, Baghdad, Iraq, 16-17 December. https://coagri.uobaghdad.edu.iq/?p=25970https://drive.google.com/drive/folders/12McvZNZ1QnFBs8UD6TUcrmJNg8wXP-f-

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ABBREVIATIONS

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ac	Acre
ACT	Australian Capital Territory
AD	Air drying
Ag plot	Agricultural plot station, University of Southern Queensland
AIP	Australian Institute of Petroleum
ANOVA	Analysis of variance
APSIM	Agricultural Productions Systems sIMulator (https://www.apsim.info/)
ASABE	American Society Agricultural and Biological Engineering
ASAE	American Society of Agricultural and Engineers
ASC	Australian Soil Classification
AUD	Australian dollar
Av. Tmax	Average of maximum temperatures
Av. Tmin	Average of minimum temperatures
Av.TR	Average of total rainfall
B ha	Billions of hectares
BBP	Bigham Brothers Paratill™
BBT	Bigham Brothers Terratill™
C	Control (no ripping)
˚C	Degree of Celsius
CHPD78	Christie's Engineering Post Driver 78
CLL	Crop lower limit
CMT	Crop module templates
CO_2	Carbon dioxide
CP40II	Cone penetrometer 40II
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSIRO AF	CSIRO Agriculture and Food
CTF	Control traffic farming

Cu	Copper
D	Implement overall draft force
D1	Deep ripping (treatment 1, 0-30 cm)
D2	Deep ripping (treatment 2, 0-60 cm)
DAP	Di-ammonium phosphate
DMRT	Duncan's multiple range test
D_{net}	Net implement draft
DUL	Drained upper limit
e.g.	Exempli gratia, meaning "for example."
ESP	Exchangeable Na percentages
FAO	Food and Agriculture Organization
g	Acceleration due to gravity
G&O	Godwin and O'Dogherty
GB	Gross benefit
GI	Gross income
GLM	General linear model
GM	Gross margin
GS 65	Growth stage code 65 of Zadoks stages for cereals
GVP_{wheat}	Gross value production of wheat
h	Hour
H	Hydrogen
HI	Harvest index
HI_{db}	Harvest index, dry basis
Hp	Horsepower
I&H cost	Insurance and housing cost
IVT	Infinitely variable transmission
JD	John Deere tractor
K	Potassium
K ha	Thousands of hectares
KMC	Kelly Manufacturing Company subsoiler
kN	Kilo newton
KPa	Kilopascal
K_{SAT}	Saturated hydraulic conductivity

Kw	Kilowatt
LL	Lower limit
LL15	Lower limit corresponding to a soil potential of 15 bar
LSD	Least significant differences
MC_{db}	Moisture content, dry basis
MC_{wb}	Moisture content, wet basis
Mg	Magnesium
M g	Millions of grams
M ha	Millions of hectares
Mn	Manganese
M Pa	Millions of Pascal
MR	Total implement motion resistance
N	Nitrogen
n	Number of observations
N_2O	Nitrous oxide
NB	Net benefit
NH	New Holland tractor
NPK fertiliser	Nitrogen, phosphorus and potassium fertiliser
NSW	New South Wales
O	Oxygen
PAWC	Plant available water content
P	Phosphorus
P_C	Crop price
P_{dp}	Drawbar power required for the implement
PO	Porosity
PTO shaft	Power take-off shaft
QLD	Queensland
R&M cost	Repairs and maintenance cost
$R_{S\&C}$	Soil and crop resistance
RTA	Roads and Traffic Authority
RTF	Random traffic farming
S	Sulphur
SAT	Saturated

SPSS	Statistical Package for Social Scientists
SSSA	Soil Science Society of America
Std	Standard deviation
TAB	Total aboveground biomass
tt	Thermal time
TVC	Total variable costs
UAN	Urea ammonium nitrate
UN	United Nations
USA	United States of America
USD	United States dollar
USDA	United States Department of Agriculture
USQ	University of Southern Queensland
V_l	Volume of liquid
V_s	Volume of soil
V	Velocity (speed)
V_c	Critical velocity
VDT	Very deep tillage
w	Width
W_d	Dried weight of sample
W_i	Initial weight of sample
WA	Western Australia
YG	Yield gains
Y_{MO}	Crop yield of management option
Zn	Zinc
ρ	Soil bulk density
γ	Bulk unit weight
δ	Angle of soil metal friction
Δtt	Daily thermal time
ϕ	Angle of internal shearing resistance

1. INTRODUCTION

1.1 Project description

Global food production must increase to meet the current growth in global food demand as a result of an increasing global population, rising demand for green energy, and changes in dietary needs (Epule & Bryant, 2015). There is an absolute necessity to increase global food production by up to 70% (Schmidhuber & Tubiello, 2007) to keep pace with rapid population growth (Tilman, Balzer, Hill, & Befort, 2011) which is predicted to reach nearly 9.7 billion by 2050 (Chelaifa et al., 2020) and roughly 11 billion by 2100 (Mountford & Rapoport, 2015; UN, 2019). Since early agricultural history to the 1950s, the global farming sector concentrated on increasing productive arable land area to enable an increase in food production (Bajželj et al., 2014; Lal, 2008; Norton, Alwang, & Masters, 2007). Then, in the late 1960s, the approach changed to improving the sustainability and productivity of existing land. Modern technologies were introduced to minimise environmental impact and meet the growing population and its food/fibre demands (Chan, 1982; Harris & Bezdicek, 1994; Pellegrini & Fernández, 2018). The techniques, efficiency and timeliness of this ideology have largely achieved the desired goal even though production improvement has experienced some restrictions.

With the beginning of the 1970s, heavily mechanized, dense and long-term cropping systems have created the two most serious obstacles to achieving high yield goals, namely the depletion of organic matter (Aguiar, Cândido, Carvalho, Monroe, & de Moura, 2013; Basamba, Barrios, Amezquita, Rao, & Singh, 2006; Dawe et al., 2000; Isbell, Stephenson, & Murtha, 1976; Janzen, Campbell, Brandt, Lafond, & Townley-Smith, 1992) and compaction (Ansorge & Godwin, 2007; Liu et al., 2017; Tullberg, 2010). Soil quality and, hence, its surrounding environmental quality comes from the availability of organic matter (Gregorich, Carter, Angers, Monreal, & Ellert, 1994; Larson & Pierce, 1991; Smith, Petersen, & Needelman, 1999) which is related to many of the soil's physical, chemical and biological characteristics (Carter, 2002). Organic matter is an indirect source of plant macronutrients such as nitrogen (N), phosphorus (P), sulphur (S) and potassium (K), as well as micro-elements like copper (Cu), zinc (Zn), manganese (Mn) and magnesium (Mg) (Cuttle, Shepherd, & Goodlass, 2003; Dalal & Mayer, 1986b). Thus, soils under unbroken cropping rotations may be high-cost yet productive (Cuttle et al., 2003; Strong, 1986), as they require considerable rates of costly N fertiliser. N is the first plant-ready component suffering deficiency as a result of reduced soil organic matter (Dalal & Mayer, 1986a; Dalal et al., 1995; Probert, Carberry, McCown, & Turpin, 1998). However, most soils under continuous production programs after fertilisation, are likely to experience a decline in yield due to compaction (Dıaz-Zorita & Grosso, 2000; Kumar, Bansal, & Phogat, 2009).

In such soils, fertilisation is likely to be ineffective as most of the applied N is lost from the soil system through emission to the atmosphere as nitrous oxide gas (N_2O) (Hansen, Bleken, & Sitaula, 2008; Powlson et al., 2012) as a result of anaerobiosis under compacted soil conditions (Breland & Hansen, 1996; Jordan, Ponder Jr, & Hubbard, 2003). Soil compaction has negative effects on the physical, chemical and biological activities of all soil textures (Gupta, Sharma, & DeFranchi, 1989; Sidhu & Duiker, 2006), but its effect may be more severe, larger, and deeper with increased clay content (Alakukku & Elonen, 1995; Chamen, Chittey, Leede, Goss, & Howse, 1990).

Historically, and as a result of farm machinery use, compaction has been a key factor affecting crop productivity (Raper & Bergtold, 2007). Currently, the influence of soil compaction is immense, and was classified as very critical by the early 2000s as a result of the introduction of heavier and wider machinery (Ansorge & Godwin, 2007; Bennett, 2016; Jones, Spoor, & Thomasson, 2003). Soil compaction is estimated to impact more than 68 million hectares (M ha) around the world (Nawaz, Bourrie, & Trolard, 2013). Therefore, various international forums have acknowledged that the remediation of soil compaction is imperative to maintaining crop yield for human and animal consumption. Consequently, soil compaction research has increased remarkably with respect to its causes, ramifications, and the efficiency of recommended modern techniques to alleviate its harmful effects on soil, plants, and the environment (Chamen, Moxey, Towers, Balana, & Hallett, 2015). In the Australian cotton industry, the introduction of on-board-module-building heavy machinery that may reach to 35 M g (Bennett, 2016; Bennett et al., 2019) has led to increased industry interest in very deep tillage (approaching 1.0 m in soil depth).

Deep tillage (Loveday, Saunt, Fleming, & Muirhead, 1970), deep ripping (Ellington, 1987), deep ploughing (Jayawardane & Chan, 1994), subsoiling (Hartmann, Blanchart, Louri, Rangon, & Bernard, 1998), or deep cultivation (Hamza & Anderson, 2002a) are synonymous. Deep tillage aims to loosen hard and compacted soil layers to or below 30 cm with a sturdy tine/s (ASAE, 1993; Manik et al., 2019), facilitating crop root growth and water movement (ASAE, 1993; Ji et al., 2014). Gardner, Nielsen, and Shock (1992), Raper and Bergtold (2007), and Manik et al. (2019) concluded that deep tillage reduces waterlogging and runoff due to improved infiltration. Campbell (1974), Reicosky, Cassel, Blevins, Gill, and Naderman (1977), Busscher, Karlen, Sojka, and Burnham (1988), and Busscher and Bauer (2003) observed that deep tilling stimulates plant roots, minimising dwarfism by reducing soil resistance to root penetration. Furthermore, Kirkegaard et al. (2014) and Dang et al. (2018) stated that the risks of continuous, traditional tillage systems on soil and crop production are highly likely to be minimised via reduction in conventional tillage associated with the occasional deep tillage practice.

Ellington (1987), Wild, Koppi, McKenzie, and McBratney (1992), and Schwab, Reeves, Burmester, and Raper (2002) acknowledged that deep tillage modifies the soil profile via the disruption of massive layers within the soil profile without causing inversion, meaning unwanted subsoil constraints are not brought to the surface. What's more, Kladivko (2001), Ceja-Navarro et al. (2010) and Ji et al. (2014) stated that deep ripping could be an effective way to restore soil fertility by increasing soil oxygen for living organisms' reproduction and activity, increasing the facilitation of soil biochemical reactions. Kayombo and Lal (1993), Bell et al. (1996), and Schneider, Don, Hennings, Schmittmann, and Seidel (2017) also highlighted that deep ripping is an effective mechanical technique for disrupting compacted soil layers and mitigating densities under different tillage and cropping systems in Africa, Australia, Europe, Asia and America.

However, deep tillage has not satisfied the ambition of many other researchers. Some studies have documented deep tillage as increasing crop production, however their documents also show that the effects are often not sustained in the long term (Bakker, Hamilton, Houlbrooke, Spann, & Van Burgel, 2007; Hamza & Anderson, 2005; Loveday, Muirhead, & Gunn, 1974; Perry, 1986; Radford et al., 2000), and may be an expensive practice compared with other tillage systems (Hamza, Riethmuller, & Anderson, 2011; Kichler, 2008; Kirby & Palmer, 1992; Sabine, 2017) or compaction mitigation strategies (Antille, Bennett, & Jensen, 2016; Lacey, Brennan, & Parekh, 2001; Patterson, Chamen, & Richardson, 1980; Zeng, Chen, & Zhang, 2017). Meanwhile, many studies have another viewpoint that effective deep ripping, like any tillage system, is the consequence of good operational management.

With suitable soil moisture, operational conditions and tine design, deep ripping is more effective, productive, long lasting and economic (through reduction of around 30% in total operation costs) through the reduction of soil pore smearing, layer stirring, tine power requirements, and increasing seedling emergence and yield (Araya, 1994b; Araya, KawanishiI, & Gao, 1983; Etana, Håkansson, Zagal, & Bučas, 1999; Lehrsch, Whisler, & Römkens, 1987; McKenzie, Abbott, Anthony, Hall, & Higginson, 1985). Moreover, Chamen (2015) confirmed that the deep ripping action may be counterproductive on crop yield responses when care is not exercised both during and after its operation. Many studies have firmly acknowledged that coupling deep tillage with other strategies such as inorganic amendment (e.g. gypsum or lime) (Bennett, Cattle, & Singh, 2015; Ellington, 1986; Hamza & Anderson, 2003; Henry et al., 2018), organic amendment (e.g. manures, compost) (Celestina, Sale, Tang, & Franks, 2017; Clark, Sale, & Tang, 2010; Gill, Sale, Peries, & Tang, 2019; Gill, Sale, & Tang, 2008), chemical fertilisers (Adcock, Wilhelm, McNeill, & Armstrong, 2006; Celestina et al., 2018; McBeath, Grant, Murray, & Chittleborough, 2010; Nable & Webb, 1992) or within the CTF system (Antille, Bennett, et al., 2016; Smith, 1995; Wesley & Smith, 1991) may benefit both soil and crops for periods of more than ten years. Making it an effective, valuable and profitable practice. Despite deep tillage being considered a strategy for sustaining or increasing agriculture productivity and profitability, its adoption requires further and broader analysis.

According to Probert, Keating, Thompson, and Parton (1995), Palosuo et al. (2011) and Challinor et al. (2014), simulation models are a powerful tool to support and improve the extrapolation, study and analytical abilities in assessing technique performance, and thus make the task of decision-making easy, and accurate. Understanding on-farm draft force requirements for owned tillage equipment plays an important role when selecting the appropriate tractor and establishing its operational efficiency. That is, reducing tractor energy, fuel consumption, working hours, costs and soil compaction, whilst achieving the required tillage goal. Correct determination has potential to improve soil properties and management, as well as the yield component, thus increasing farm profit.

The single tine model developed by Godwin and O'Dogherty (2007) (G&O) predicts the forces affecting tillage equipment in relation to the tillage working elements of geometry and soil condition. It is the most widely accepted model for tillage purposes because of its simplicity, comprehensiveness, ease of running and ability to compare a variety of integrated tine designs with various soil conditions (Ahmadi, 2017; Chen, Munkholm, & Nyord, 2013b; Keppler, Hudoba, Oldal, Csatar, & Fenyvesi, 2015). However, there is a paucity of information relating to very high clay content soil systems and the performance of the G&O model (Bennett, Jensen, Antille, & Baillie, 2016). In order to apply this model for the majority of Australian soils, validation is required. Besides, on-farm prior knowledge of the strategy effects on soil properties and yield component under the long-term climates influence has a key role in evaluating the candidate strategies and selecting the most efficient among them.

Agricultural Productions Systems sIMulator (APSIM) (Keating et al., 2003; McCown, Hammer, Hargreaves, Holzworth, & Freebairn, 1996) is one of the few available cropping software system models capable of simulating crop growth minutely, water equilibrium, soil carbon and nitrogen, climate, cropping history, and crop/soil management function, which operates on a daily time step at a bay scale or small field, and in either individual crop or cropping system (Akponikpè, Gérard, Michels, & Bielders, 2010; Connolly, Freebairn, Bell, & Thomas, 2001; Moeller, Pala, Manschadi, Meinke, & Sauerborn, 2007; Probert, Dimes, Keating, Dalal, & Strong, 1998; Williams et al., 2015).

Soils with high clay content are dominant in major areas of eastern Australia (especially Queensland and New South Wales) (de Vetten, 2014; Freebairn, Ward, Clarke, & Smith, 1986; Laffan, 1988) where row and cereal crop production are used (Hulme, McKenzie, MacLeod, & Anthony, 1996; Martin & Cox, 1956). In these regions, crop yield has experienced a decline since 1975, due to depletion of soil organic matter content and increased bulk density, as a result of extensive, intensive and largely uninterrupted agricultural activities (Hulugalle & Scott, 2008). Acceptance of deep tillage by farmers is impeded by the excessive draft force requirements identified since it was first applied in 1980 (McKenzie et al., 1990). This, in turn, has led to a lack of research, especially by those documenting the relationship between different tillage depths and crop yield. In addition, with rapidly escalating fuel prices, deep tillage is considered a costly process involving high fuel consumption (Kirby & Palmer, 1992; Sabine, 2017).

Deep tillage is a strategy of soil and agricultural production sustainability rather than a consistent operational task, and its real returns are likely to materialize in the longer term if managed properly (Chamen et al., 2015). Nevertheless, its relatively high overall expense has resulted in the reluctance of many agricultural practitioners to adopt it, especially when the first yield does not compensate the operating energy costs. Consequently, deep tillage does not appear to have been investigated in terms of its benefits and potential costs in Australia.

As motivation and value proposition is largely lacking, a lack of decision-making models and validation studies that support farm management to make deep ripping adoption decisions has resulted. Therefore, the aim of this investigation is to determine if a relationship between deep tillage depths, yield, and implement draft force exists, with optimum urea fertiliser rates (sometimes) for cereal crop/s. And if so, to evaluate the cost-benefit of deep tillage. The empirical data of this study (soil physical and hydraulic properties, seed rates, trials activities (e.g. tillage, sowing, and fertilising operation etc.)) were used to parameterise the model to quantify likely long-term effects of deep ripping depth levels on crop component yield based on published approaches of crop performance simulation.

For this purpose, the APSIM model (Holzworth et al., 2014; Keating et al., 2003; McCown et al., 1996) was used to predict the likely effects of deep tillage systems on the yields of grain and biomass of winter wheat and summer sorghum, which are the most common crops in southern Queensland. This work also seeks to evaluate the G&O model (Godwin & O'Dogherty, 2007) and its suitability for predicting the draft force requirements of a single tine ripper in soft, heavy and dense soils (with a high clay content). The soil physical and mechanical properties as well as the tine design parameters, and operational conditions of the adjacent field trials to crop/s experiments, were employed in feeding and operating the model. Finally, the measured values of the required draft force and crop/s yield components were compared against the G&O and APSIM models' predicted outcomes to assess their validity.

1.1.1 Aim

The overall aim of this study is to technically and economically evaluate deep ripping systems for high clay content soils. In doing this, it will be necessary to study the effect on soil physical properties and arable crop/s yield components. Additionally, assessing the validity of the G&O and APSIM models, to reflect trial results and subsequently allow extrapolation of results for future planning, is a requirement of the work.

1.1.2 Objectives

1. Evaluation of deep tillage impact on soils, crops and benefits at two Queensland farms with high clay content soils
2. Investigate the G&O single tine model's validity in two Queensland high clay content soils
3. Determination of deep tillage systems effect on crop performance in two Queensland high clay content soils under long-term climatic conditions using the APSIM model
4. Validation of APSIM predictability for deep tillage systems' effects on sorghum and wheat yields in two Queensland high clay content soils.

1.2 Thesis structure

A summary of the methodological approach and the thesis structure is shown in **Figure 1.1**. Global agricultural sector policies, adoption reasons and challenges are outlined in the introduction to this study (**Chapter 1**).

Chapter 2 provides a review of the literature related to the main aim and objectives of this research. Therefore, Chapter 2 focuses on the impact of modern cropping strategies and technologies on soil structure, fertility and production. The Australian agricultural sector's role in supporting global food security and the national economy through a simplified review of cultivated areas and crops, applied fertilisers, production and annual profits, is the topic with which the literature review begins. This is followed by a review of Vertosols and Ferrosols clayey soil, wheat and sorghum crops, inorganic fertilisers and N fertilisers' areas, importance, and features. Soil compaction definition, causes, procedures for mitigation and evaluation, deep tillage advantages and disadvantages, means of evaluation, required draft force and cost and benefits make up the body of the review. Before the conclusion, the G&O and APSIM models are considered to support farm decision-making.

Field experiments, their locations, crops, stages, studied parameters and equations, model validation steps (modelling work), and statistical analysis software are mentioned in detail in **Chapter 3**. The results and discussion are presented in **Chapter 4**. The overall conclusions of the main findings from the individual experiments are presented in **Chapter 5**. Finally, a set of practical recommendations and future work is offered in **Chapter 6.**

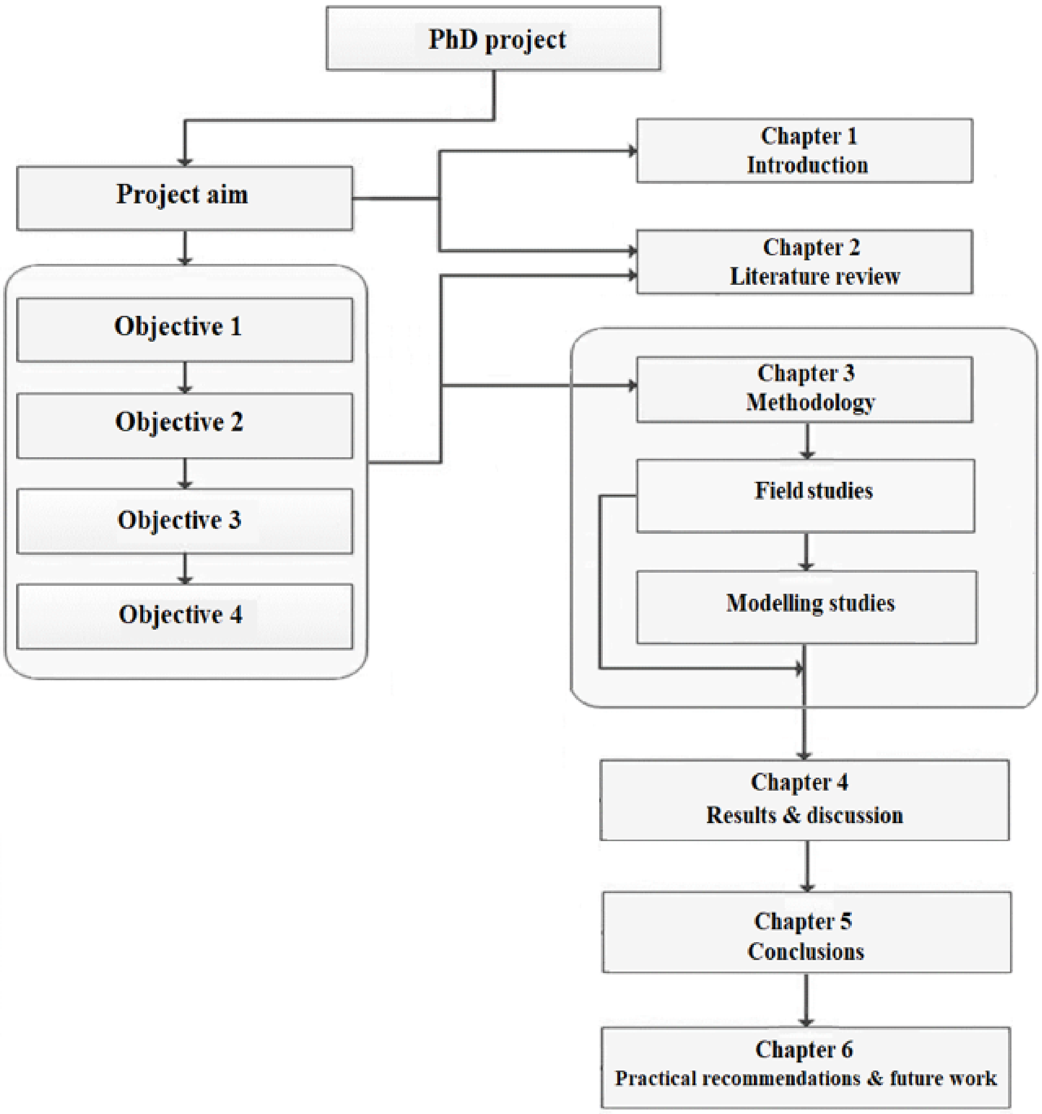

Figure 1-1: Outline of the research methodology and summary of thesis structure

2. LITERATURE REVIEW

2.1 Introduction

This chapter is divided into several sections based on the objectives and aims of this study. Section 2.2. reviews the Australian agricultural sector with regard to the agricultural land area in general, and Vertosols and Ferrosols clayey soil in particular, the number of agricultural businesses, fertilised area and fertiliser use, crop production and cereal crops in particular, economic values and contribution to the annual Australian economy as well as to global food security. The section ends after reviewing the above themes, but for the Queensland agriculture sector (based on ABS estimates and scientific research articles).

Sections 2.3 and 2.4 review two common clay soils (Red Ferrosols and Vertosols) regarding their areas and location in Australia and Queensland; their common crops, features and restrictions. The winter wheat and summer sorghum crops are dealt with in Sections 2.5 and 2.6. Inorganic N fertiliser: why to apply, types, application rates and fertilised areas, are highlighted in Section 2.7. Section 2.8 addresses soil compaction: its definition, causes, indicators, and consequences for soil and crop components, with some studies on these. Tillage practice definition and objectives commonly used in Australia, are discussed in Section 2.9. Section 2.10 discusses one of the tillage systems used internationally and in Australia; namely deep ripping. This section deals with advantages of deep ripping, its limitations and some indications of its effect on improving soil properties and crop productivity. Section 2.11 shows how deep ripping is improving Australian Vertosols crop productivity by addressing its subsoil constraints.

Cone index or soil penetration resistance or soil strength as an indicator of assessing deep tillage performance, its costs and benefits and the power required to pull it are covered in Sections 2.12, 2.13 and 2.14, respectively. The G&O single tine force prediction model and its output and input equation parameters are reviewed in Section 2.15. Section 2.16 gives a historical review of the subsoiler tine design role on increasing tillage operational efficiency due to reduced draft force requirement and fuel consumption as well as improving the fertiliser injection process. APSIM, one of the crop performance models, is discussed in detail: its uses and modules are presented in Section 2.17 and 2.18. Section 2.19 concludes the chapter.

2.2 Overview of Australian and Queensland agriculture sector and grain industry

Australian agricultural production systems are currently under threat from three main environmental factors: high CO_2 concentrations in the atmosphere, increasing frequency of droughts, and more frequent heat waves (O'Leary, 2019). However, the Australian agricultural sector is continuing to introduce new maiden hectares either within existing farms expansion plans or through the employment new agricultural businesses. According to the Australian Bureau of Statistics (ABS, 2020a), on 30 June 2019, there were 384 M ha of agricultural land in Australia. Nearly 7680 K ha (+2%) were included in agricultural production compared to the 2017-18 estimates (378 M ha). According to the 2020a statistical bulletin, this coincided with an increase in the number of agricultural businesses. On 30 June 2019, the total number of agricultural businesses was approximately 89400, an increase of 5% compared to the 2017-18 estimates (85000 agricultural business).

Regards to the land allocated to crop production, additional areas of approximately 714,702 ha were planted by farmers during the agricultural season of 2018-19 bringing the total to 31074000 ha compared to the 2017-18 crop producing land which was around 30359298 ha (ABS, 2020a). Further, the farmers of southern Australia added more productive land than any other region with approximately 57176 ha added to crop production in 2016-17, followed by Western Australia which added about 28588 ha during the same year (ABS, 2018b). Around 20209000 ha, or approximately 65% of the 2016-17 total cropping land area, were devoted to cereal and oilseeds crop production, whereas these areas represented almost 61% (about 18389000 ha) of the total agricultural production areas during the 2015-16 production season (ABS, 2018c) (Figure 2-1).

Annually, agricultural businesses contribute significantly to supporting the Australian economy. According to the latest issue of the Australian Bureau of Statistics, released on 28/05/2020, the gross value of the Australian agricultural sector during 2018/19 was about AUD60 billion, of which the proportion of crop production was nearly half (AUD30 billion) (ABS, 2020b). According to the same ABS document, the value of grains, oilseeds and legumes produced in NSW and Queensland (which accounts for more than half of crop production's total value) decreased significantly during the 2018-19 season due to drought conditions (Figure 2-2).

Of the top three cereals (wheat, rice and maize), wheat is the main provider of calories and protein for the world's population (Cai et al., 2019). Wheat cultivation in Australia is long-established, spanning more than two hundred years (Shewry, 2009), giving farmers enough experience of how to deal with, and to become, one of the top wheat exporting countries globally (Cai et al., 2019; Smith, 2017; Workman, 2017).

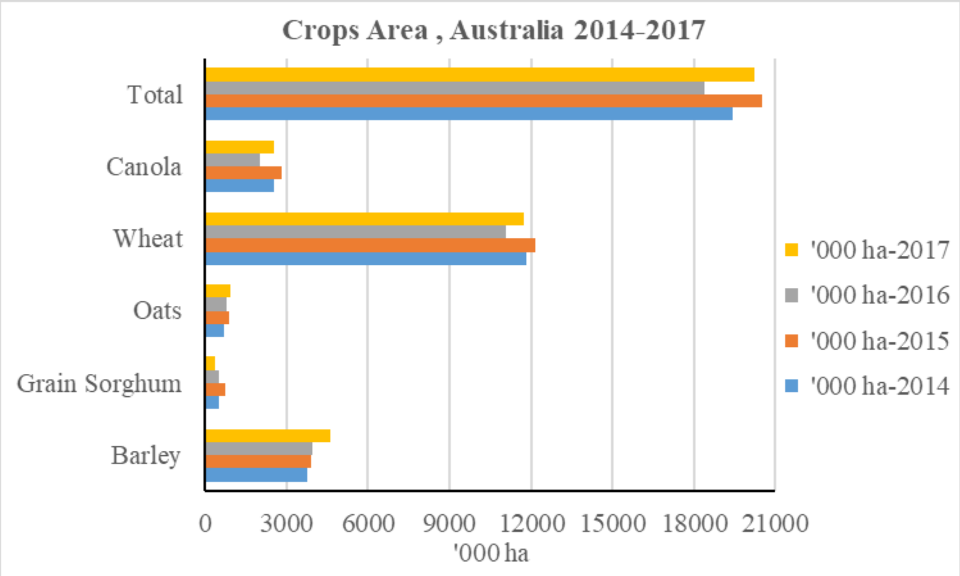

Figure 2-1: Area (ha) of crops during 2014-17 (ABS, 2018c)

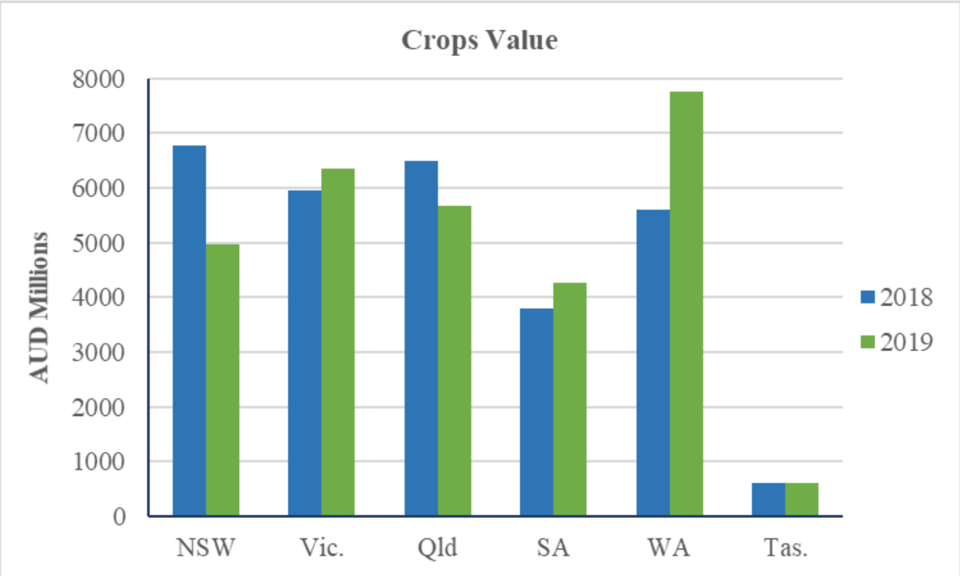

Figure 2-2: Crops value for each state in 2018 and 2019 (ABS, 2020)

Australia contributes over 12% of global wheat exports and plays a key role in future global food security (Gobbett et al., 2017). Australian wheat is also characterised as the largest annual crop in terms of allocated area (about 55% of Australian cropland) (ABS, 2018b; Fischer, Byerlee, & Edmeades, 2014; Van Ittersum, 2016), tonnage and value (ABS, 2020a, 2020b; Wang et al., 2018). However, in 2018-19, wheat harvested in the eastern states was significantly affected by continuing drought, making this the lowest level since 2007, with a total of 18 million tonnes (ABS, 2020a), see Figures 2-3 and 2-4.

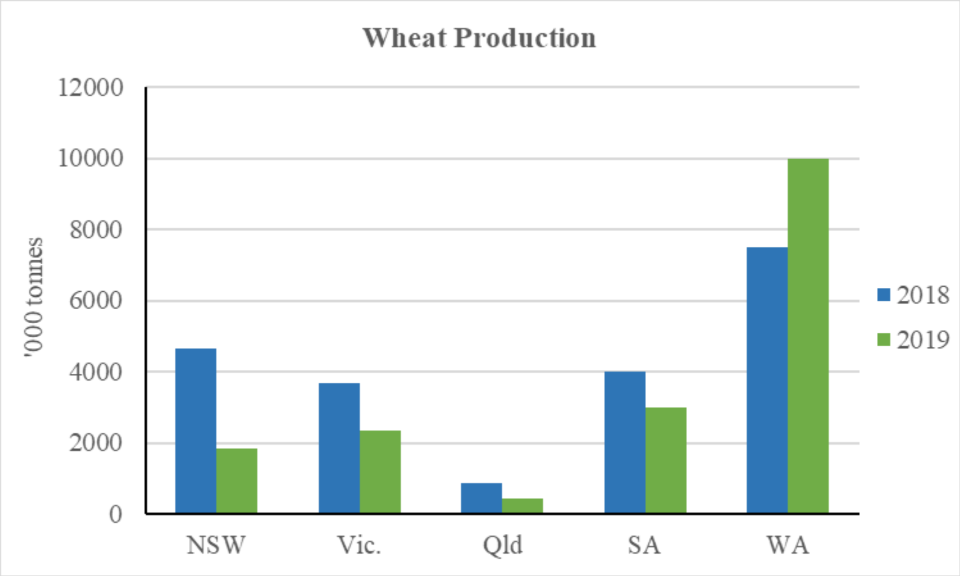

Figure 2-3: Wheat production per state in 2018 and 2019 (ABS, 2020a)

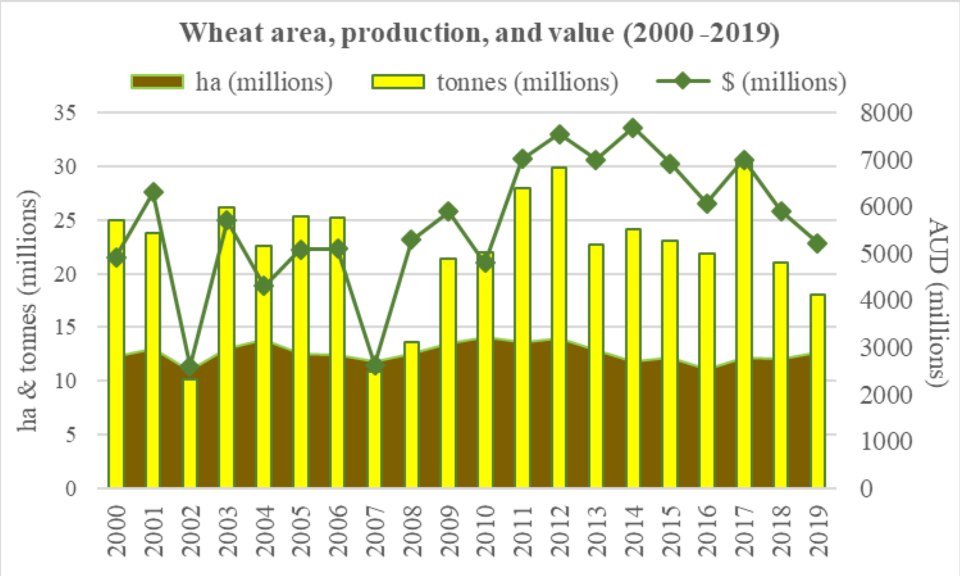

Figure 2-4: Wheat planted area (ha), grain yield (tonnes) and value (AUD) from 2000 to 2019 (ABS, 2018a, 2018b, 2020a, 2020b)

Although wheat productivity decreased by 16% during the 2018-19 season compared to the 2017-18 season (Figure 2-4), it remained the largest crop in terms of production by 18 million tonnes or 27% of total grain industry tonnage, representing 66 million tonnes (ABS, 2020a). The ABS (2020a), also estimated that in 2018-19, approximately 12.7 million hectares were sown with wheat seeds, representing around 41% of the area allocated to all crops, and 58% was allocated to (31 million ha) other cereals, oilseeds and legumes (broadacre) (22 million ha). According to the ABS (2018a, 2018b, 2020a, 2020b), the average wheat production per hectare in Australia during the last 20 years (from 2000 to 2020) ranged from 1.3 to 2.2 t/ha.

Furthermore, the 2018-2019 wheat gross value production (GVP_{wheat}) was around AUD 6 billion (Figure 2-4); almost one-fifth of the total crop gross value and more than half of the broadacre crop total value (ABS, 2020b). Large agricultural areas in Queensland and NSW have experienced drought throughout the 2018-19 season, so their wheat witnessed a significant decline in its production level compared to the previous season, while the Western Australia (WA) state came first, experiencing bumper production during the same year (Figure 2-3) (ABS, 2020a). Generally, wheat is produced in all types of Australia arable land, but the wheat belt zone is the main source of nearly two-thirds of country wheat production (Stephens & Lyons, 1998) representing a narrow crescent of land to the east, south east and south west of Queensland, New South West, South and Western Australia (Chenu, Deihimfard, & Chapman, 2013) (Figure 2-5).

Sorghum has gained global attention as an agro-industrial crop, as it is a source of food and feed production, as well as an energy source for integrated bio-refineries (O'Hara et al., 2013). Moreover, it is a vital regulator of many diseases that settle on arable soils and an active barrier to wind and water erosion by providing stubble cover (Komolong, Chakraborty, Ryley, & Yates, 2002). That is why since the 1980s, Australia has been intensifying field, laboratory and physiological research to keep sorghum production stable and positive compared to other cereal crops such as wheat, maize and rice, which have witnessed a reduction in global attention to ways of increasing production (Potgieter et al., 2016).

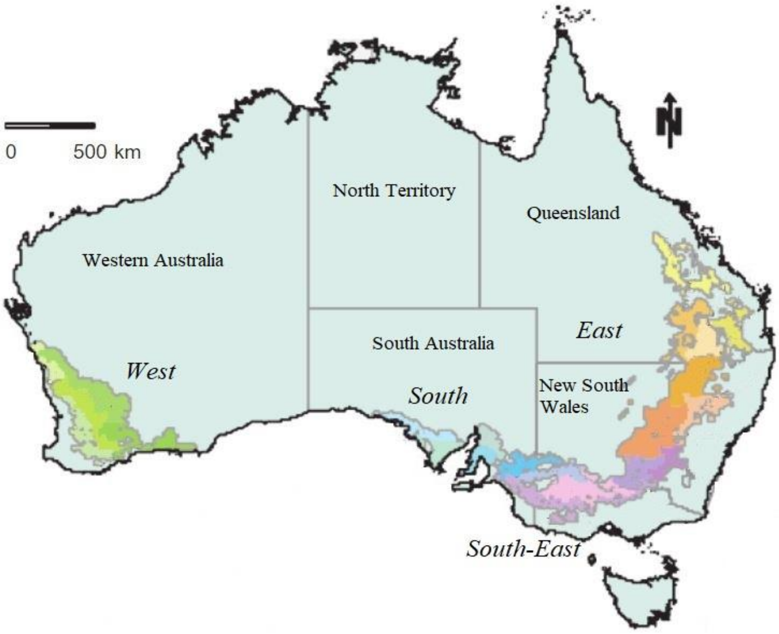

Figure 2-5: The four cropping areas of the Australian wheatbelt: the “West” area (green colours), “South” (blue), “South-east” (purple) and “East” (orange) (Chenu et al., 2013)

Globally, Australia is ranked fifth in sorghum production, and its production is generally concentrated in central and southern Queensland (70%) and northern NSW (30%) due to the predominance of summer rains. Sorghum is the main summer cereal crop of both states (Komolong et al., 2002). Its production is not limited to these two states. Pratley (1980) stated that sorghum is often grown as a rotating crop with winter cereal crops in some regions, especially those producing wheat. (Figure 2-3).

According to ABS (2018a and 2018b) estimates, the average production of sorghum per hectare in Australia over the past 19 years (from 2000 to 2018) has fluctuated from 3.4 tonnes/ha to 2.4 tonnes/ha. The same sources estimate that the annual average national production of sorghum until 2016 has fluctuated from 2.6 M tonnes/year to 1.5 M tonnes/year (Figure 2-6). Also, this national production was the result of cultivating lands whose average annual areas ranged until 2016 from 0.81 M ha to 0.57 M ha.

However, the recent exceptionally warm Queensland summers, below average rainfall and devastating cyclones (such as Cyclone Debbie in 2017), have adversely affected the growth, and even continuation, of usual production rates. In addition to the severe weather conditions, the recent fall in sorghum purchase price by the state, has pushed the majority of farmers to plant alternative broadacre crops (ABS, 2018a), thus its designated cultivation areas fell from 0.52 M ha to 0.37 M ha and then to 0.44 M ha in 2016, 2017, and 2018, respectively (Figure 2-6). Consequently, the national sorghum production level decreased from 1.8 M tonnes to 0.994 M tonnes and then to 1 M tonnes annually during the seasons of 2016, 2017 and 2018, respectively (Figure 2-6). As expected, the average economic return decreased from AUD428 million during the period 2000 to 2016 to AUD 231 million for the years 2017 and 2018 (ABS, 2019).

Inorganic fertiliser, which also known as synthetic, mineral or commercial fertiliser, has become one of the most important major N sources for both cropping and pasture systems soils globally (Galloway, Leach, Erisman, & Bleeker, 2017). In regions with sufficient rainfall, Australian farmers' keenness to apply mineral fertilisers has increased remarkably due to its positive impact on productivity (Dharma, Shafron, & Oliver, 2012). Therefore, the percentage of Australian farms that apply commercial fertilisers has increased from 28% to 76% during the period from the 1990s to the 20210s (Stott, Malcolm, & Gourley, 2016).

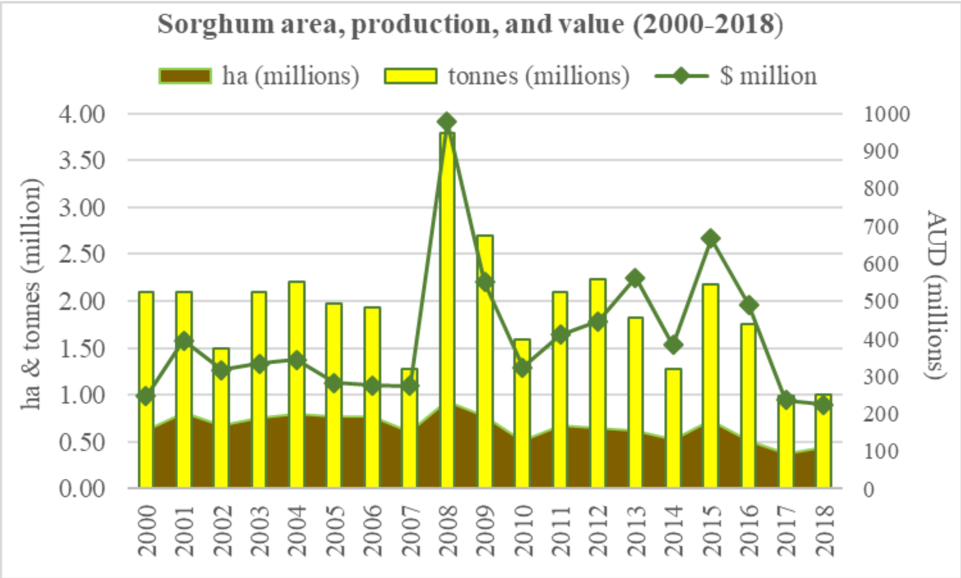

Figure 2-6: Sorghum planted area (ha), grain yield (tonnes), and value (AUD) from 2000 to 2018 (ABS, 2018a, 2018b, 2019)

As the population grows, intensive and continuous cropping production to meet the global food demand will become a necessity. For this, Gourley, Hannah, and Chia (2017) expected that the soil supply source with direct or indirect N (inorganic fertiliser) will witness considerable order in the immediate future.

The latest Australian Bureau of Statistics issue estimated that around 57300 agricultural businesses spread over Australia up to 30 June 2017, had applied about 5 M tonnes of inorganic fertilisers to a total of 50 M ha (ABS, 2018b). According to same source, 37% of Australia's total fertilised land (approximately 19 M ha) is controlled by Western Australian agricultural businesses. This source also mentions that 20% of the total amount of fertiliser (about 1 M tonnes) was applied by Western Australian and New South Wales' (including Australian Capital Territory (ACT)) agricultural businesses. Figure 2-7 shows all fertiliser applied in tonnes (‘000) until 30 June 2017 by Natural Resource Management regions (ABS, 2018b).

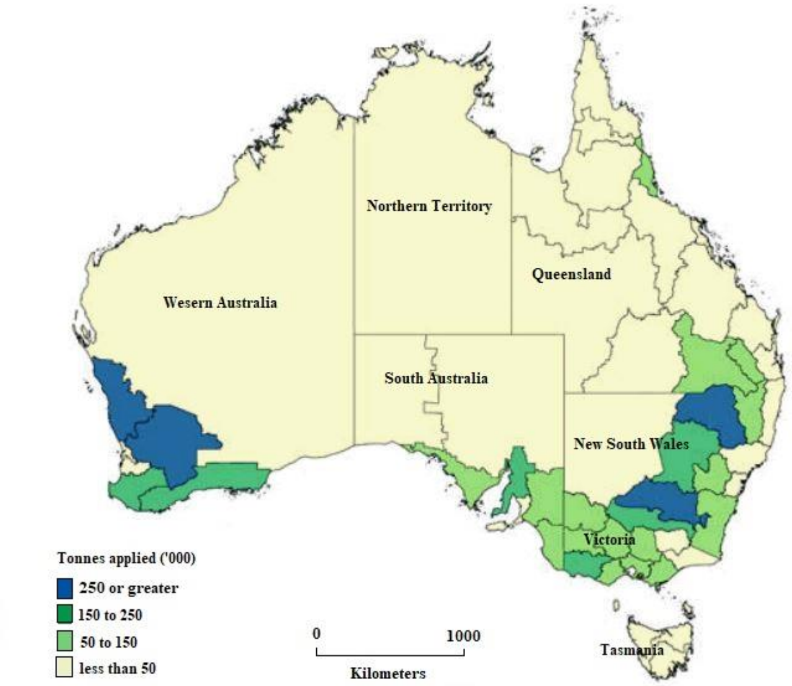

Figure 2-7: All fertiliser applied in tonnes (‘000) throughout Australia until 30 June 2017 (ABS, 2018b)

Figure 2-8 shows the estimated average of fertiliser use according to the last three releases of ABS (2016b), ABS (2017b), and ABS (2018b). Ammonium phosphate continued to be the most widely applied fertiliser in terms of area with an average of 13522 K ha, and average amount of 1058 K tonnes. Although it comes after ammonium phosphate in terms of the average area applied to during the years 2015, 2016 and 2017, with 11502 K ha, urea tops the list of synthetic fertilisers in terms of amount applied during those three years with 1403 K tonnes (Figure 2-8) and the number of businesses using it (ABS, 2018b).

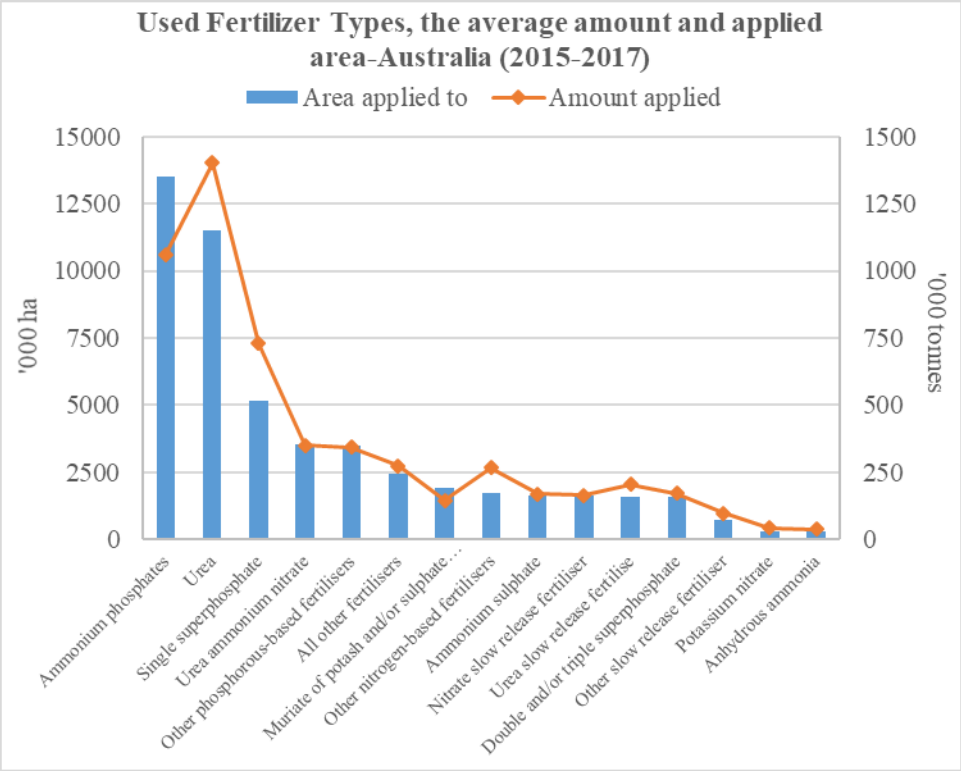

Figure 2-8: Fertiliser types and average of the applied amount and area throughout Australia from 2015 to 2017 (ABS, 2016b, 2017b, 2018b)

Nitrogen based fertiliser, either liquid form such as urea ammonium nitrate, or dry texture (granular), like urea and ammonium phosphates, is the most commonly used fertiliser by Australian farmers either by broadcasting on the surface or drilled below the surface within the root zone (ABS, 2015). Figure 2-9 shows, in descending order, the states/territories in terms of land area fertilised with nitrogen based-fertiliser according to the estimates of ABS (2016b) on 25 May 2016.

Globally, clay soils constitute a large proportion agricultural land, including pasture land (Waudby & Petit, 2017). In the Deccan Plateau of India, eastern Africa, South America and parts of eastern China, clay soils cover more than 220 M ha, whereas these soils occupy over 80 M ha in eastern and arid central Australia (Gizachew & Smit, 2012; Isbell, 1996; Liu et al., 2010). Therefore, Australia has the largest diversity and area of these soils when compared to any country in the world (Waudby & Petit, 2017). Vertosols and Ferrosols (which form the largest percentage of clay) are the main soil types in the Australian soil classification orders which constitute more than 88 M ha (11.5%) and 6 M ha (0.8%), respectively of Australian soil (768.8 M ha) (Ashton & McKenzie, 2001) (Figure 2-10). Because of their favourable agricultural characteristics, they have been used extensively in agricultural production (Cogle, Keating, Langford, Gunton, & Webb, 2011; Connolly et al., 2001).

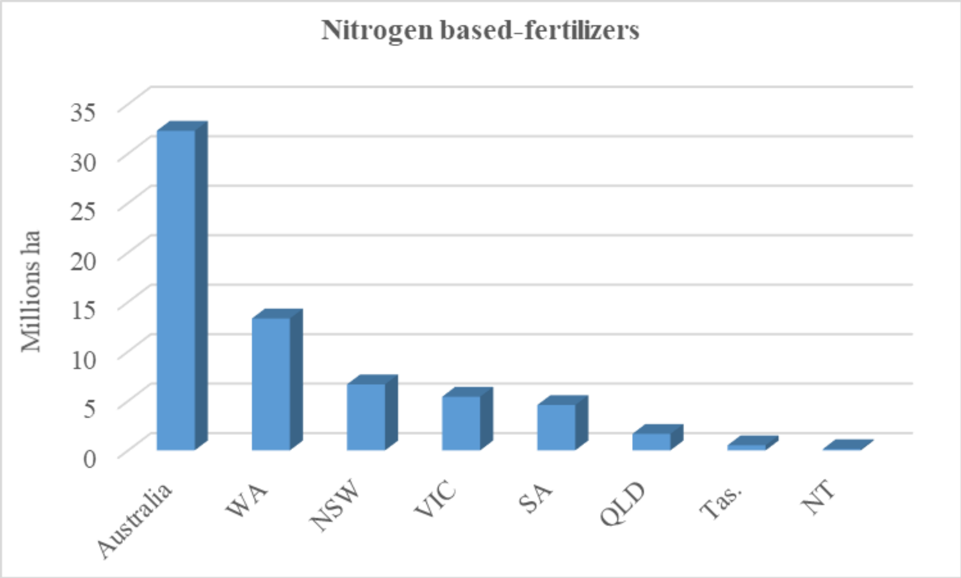

Figure 2-9: States/territories' land area fertilised with nitrogen-based fertiliser (ABS, 2016b)

According to ABS (2018a), in the middle of 2017, Queensland had the highest proportion of agricultural land, with 173065 K ha, of which 137955 K ha were used for grazing. This represents approximately 80% of the state's total land area, so Queensland is considered the largest contributor to grazing land (ABS, 2018b), while the area used for cropping is around 2605 K ha which represents approximately 1.5% of the state's total land area. Furthermore, the same statistical bulletin estimated that the area designated as non-agricultural land is around 32505 K ha which represents approximately 19% of the total Queensland land area. Its area includes a variety of soil orders based on the Australian Soil Classification system (ASC) (Figure 2-11). Vertosols (Southeast and Southwest Queensland) and Ferrosols (North and Southeast Queensland) soils are the most common soils extensively devoted to agricultural production across the state because of their plant-appropriate properties (Bell, Bridge, Harch, & Orange, 2005; Freebairn et al., 1986). Vertosols make up around 33% (50 M ha) of Queensland soil types (Weston, Harbison, Leslie, Rosenthal, & Mayer, 1983) while Ferrosols, despite their limited area, are considered an important Queensland agricultural soil (Kent & Tanzer, 1983; Laffan, 1988; Malcolm, Nagel, Sinclair, & Heiner, 1998).

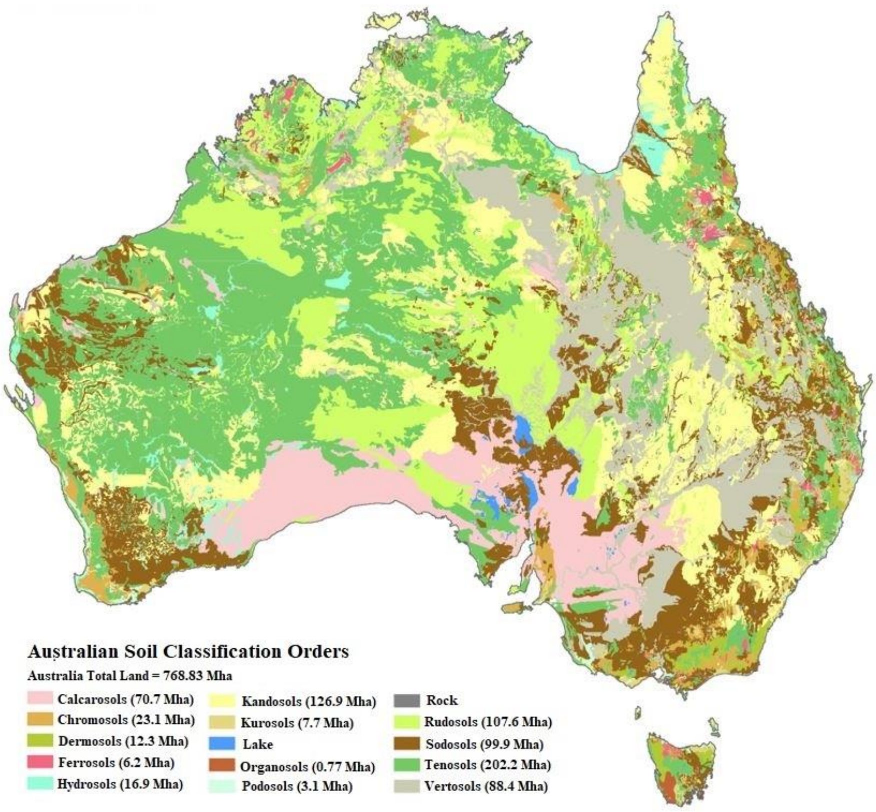

Figure 2-10: Australian soil classification orders (Ashton & McKenzie, 2001)

Queensland comes fourth after Victoria, New South Wales and Western Australia in terms of the fertilised land area (around 2.7 M ha) and used less than 50 to 150 K tonnes of fertiliser (ABS, 2016b, 2017b, 2018b) (Figures 2-7 and 2-9). The ABS (2017b) arranged Queensland crops in descending order based on their cultivated area as follows: wheat, sorghum, sugar cane, cotton, oats and maize. It estimated that approximately 454545 ha of Queensland was planted with sorghum as of mid-2016; almost half of the estimated wheat area (about 890910 ha). Queensland was also classified as the largest Australian state that produces sorghum, with an annual average production of 1315 k tonnes (ABARES, 2016) (Figure 2-12). However, as a summer crop, it is heavily susceptible to overly warm conditions. Thus, the hot and dry Queensland weather, in addition to the low sorghum purchase prices, have recently produced bad results (ABS, 2018a). As a result, the Queensland production of sorghum decreased during 2015 to 2016 and then in 2017 from 1.3 M tonnes to 1.2 M tonnes to 0.612 M tonnes, respectively (ABARES, 2016; ABS, 2016a, 2017a, 2018a).

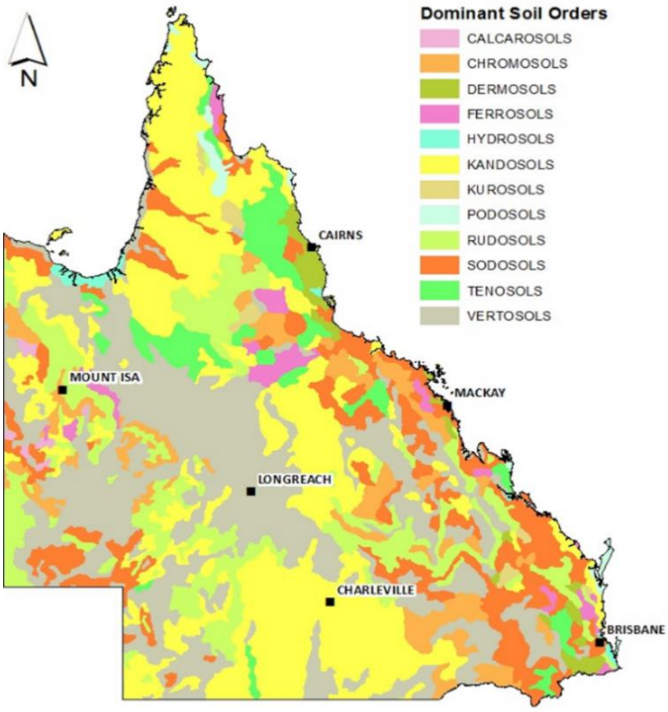

Figure 2-11: Queensland soil orders based on the Australian Soil Classification system (ASC) (https://www.qld.gov.au/environment/land/management/soil/soil-testing/types)

As for wheat production, the state's total production up to 2016 fluctuated between 0.930 M tonnes to 1.7 M tonnes per year with an average annual production of 1.3 M tonnes (ABARES, 2016) (Figure 2-12). However, unseasonable conditions including below average spring and summer rainfall, particularly during 2017-18 and 2018-19, resulted in poor wheat yields (800 K tonnes and 533 K tonnes, respectively) (ABS, 2020a), (Figure 2-3). Therefore, the total gross value of Queensland crops during 2018-19 declined 12% to AUD5.6 billion compared to the 2017-18 season (ABS, 2020b) (Figure 2-2).

From the above, it can be seen that the agriculture sector has an effective role, not only in supporting the economy and ensuring Australian food security, but even in supporting global food security by providing a large part of the global food requirements. However, it is noticeable that the agricultural sector (in general) has recently started to face very severe weather as a result of global warming, which is caused by increasing population growth and pollution sources. Not only that, the population revolution has also pushed most agricultural businesses to increase production levels through intensive and continuous cropping and introduce new, bulky and wide machinery with huge production capacities. Adopting this approach with the bad weather conditions have produced a serious dilemma that was not previously classified as a real problem, namely soil compaction.

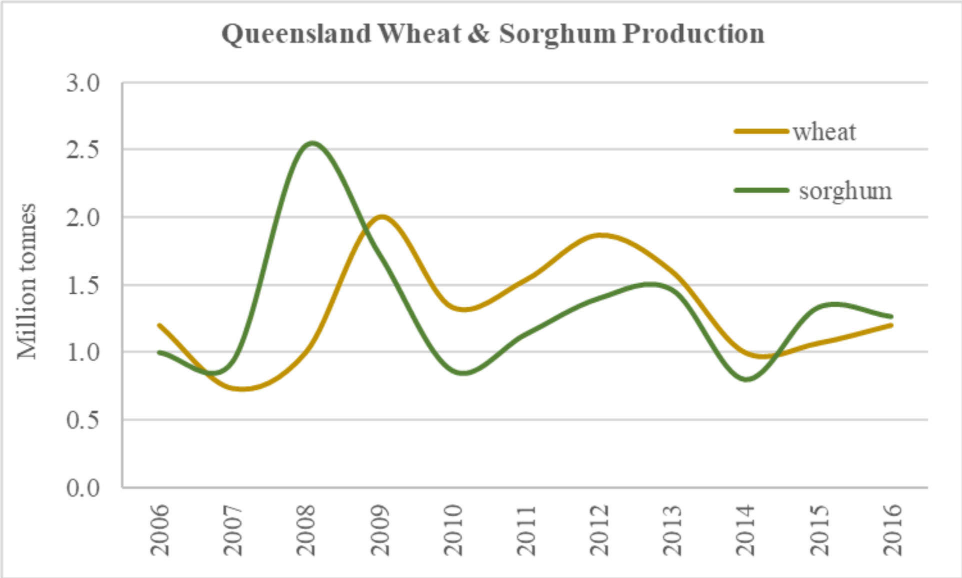

Figure 2-12: Queensland' wheat and sorghum production from 2006 to 2016 (ABARES, 2016)

Compaction has become a common soil attribute so long as land has been devoted to agricultural activity (grazing or cropping). It cannot be completely eliminated, but can be mitigated (Liu et al., 2017). As a result of its relatively smaller particles, construction nature and texture softness, the clay soil is one of the easiest soils to compact under external influence and inappropriate moisture (de Lima, da Silva, Giarola, da Silva, & Rolim, 2017). It is what most researchers attribute to world agricultural production decline in general, and Queensland in particular, as clay soil occupies a large proportion of agricultural land area. Despite the seriousness of this issue and its direct relationship to the existence of mankind and animals, agricultural knowledge still suffers from a severe shortage in relevant investigative research. Vertosols and Ferrosols are common clay soils in Australia and in Queensland (Davies, Armstrong, Macdonald, Condon, & Petersen, 2019), and they are addressed in some detail in the next section.

2.3 Red Ferrosols

Red Ferrosols are important agricultural soils in Australia in general (Cotching, 1995), and Queensland in particular (Cogle et al., 2011; Kent & Tanzer, 1983; Laffan, 1988; Malcolm et al., 1998). At the beginning of the 20th century, these soils were devoted to grazing, dairy pasture and crop industries, but rain-fed cropping exploitation has increased since the 1960s (Cogle et al., 2011).

Until the early 1950s this soil was known as Red Loams according to the first map of Australian soil by Prescott (1931); acidic red soils developed from basalt. In 1953, when Stephen published the Australian Soil Manual, the name officially changed to Krasnozem as a red to brown, acidic, strongly structured clay soils (50-70% clay) (Stephens, 1953). The Australian Krasnozems were classified as Oxisols and Alfisols according to Taxonomy (1975), Ferralsols in the FAO-UNESCO scheme (Isbell, 1994), and Red Ferrosols according to the new Australian classification (Isbell, 1996). Fine, friable, stable structure and high infiltration capacity, when uncropped (Shepherd & MacNish, 1989), they tend to degrade to a massive structure and low infiltration when continuously cropped (Bridge & Bell, 1994). Iron-rich (Webb, Grundy, Powell, & Littleboy, 1997), and non-shrink-swell with medium to high Plant Available Water Content (PAWC) (Connolly, Freebairn, & Bridge, 1997) represent the general characteristics of these soils.

Red Ferrosols appear in eastern Australia, northern Queensland and Tasmania in a rainy zone ranging from 1000 mm to 4000 mm. They are also found in some relatively drier subtropical areas of southern Queensland such as Toowoomba (970 mm) and Kingaroy (780 mm) (Isbell, 1994). Despite their limited area, these soils have been used extensively in agricultural production because of their favourable agricultural characteristics. Red Ferrosols are widely used for peanut, sugarcane and horticultural crops (Connolly et al., 1997), vegetable production (McPhee, Aird, Hardie, & Corkrey, 2015), and summer grain legume and cereal grain crops (Bell et al., 2005).

During the sixth decade of the twentieth century and due to excessive cropping, these soils began to lose one of their most important characteristics: capacity for rain water infiltration. Water infiltration is a soil drainage function which is a key factor in the sustainability of rain-fed agriculture. Thus, since the 1970s, these soils have been subjected to intensive study by many researchers (Isbell, 1994). Bell, Bridge, Harch, and Orange (1997) and Bell, Moody, Connolly, and Bridge (1998) attributed the Red Ferrosols' low infiltration to: 1) crusting of the soil surface due to decreasing labile organic carbon and 2) lowering hydraulic conductivity of down soil layers due to subsoil compaction.

With regard to organic matter, regardless of category, soil with elevated organic matter is less subject to compaction (Thomas, Haszler, & Blevins, 1996) due to improved drainage conditions (Dıaz-Zorita & Grosso, 2000; Kumar et al., 2009) and increased elasticity and/or increased deformation resistance (Soane, 1990). Whereas Smith, Johnston, and Lorentz (1997) stated that the compactability of moistened clayey and silty clay soils is likely to be less when the organic carbon content rate is highest. With cultivation of virgin Red Ferrosols, the surface organic matter (0-10 cm) drops from 3.88% to less than 2% (Isbell et al., 1976; Warrell, Cannon, & Thompson, 1984). Moreover, the top (15 cm) of red Ferrosols shows declines in microbial biomass carbon and soil organic carbon of 60% and 30% when harnessed to continuous cropping (McPhee et al., 2015). Also, the soil tests of (Connolly et al., 1997) showed that Red Ferrosols soil organic carbon decreased from 4% to 2% with increasing depth level from 0 - 10 cm to 10 - 20 cm. Consequently, the likelihood of compaction could be high since the availability of organic matter play a key role in the amendment soil physical properties.

With regards to subsoil compaction, the frequent use of rotary and disc tillage equipment was the prevailing practice by Queensland farmers in preparing seed beds, producing surface fragility and subsurface compaction of these soils. Bridge and Bell (1994) have shown that, for these soils, compaction may reach up to 60 cm which in turn leads to diminishing plant water use by 30%. Consequently, with severe storms at the start of winter and heavy rainfall in the summer which is the dominant Queensland climate, vast amounts of the fragile Red Ferrosol surface is lost as a result of high water runoff and wind erosion (Cogle et al., 2011). Cogle et al. (2011) gave an example of conventionally cultivated Ferrosols in the Atherton and Herberton shires (Queensland), experiencing up to 405 t/ha loss after the storm events of 21/11/85 to 26/11/85.

The reduction in fertility and crop yield of Red Ferrosols soils is significantly correlated to compacted subsurface layers due to continual conventional tillage and traffic practices (Bell, Harch, & Bridge, 1995; Bridge & Bell, 1994; Cotching, Sparrow, Hawkins, McCorkell, & Rowley, 2005). Ripper use is an efficient strategy for improving the physical properties of compacted Red Ferrosols (Bell et al., 1997).

Compared to other soils, Red Ferrosols possess greater pliability to negative changes in soil condition due to intensive production practices (Bell et al., 1997). Nevertheless, loss of organic matter, soil erosion and compaction are potential constraints to long-term productivity (McPhee et al., 2015).

In compacted Red Ferrosol under continuous cropping in the rain-fed, inland area of southern Queensland, deep ripping efficaciously disrupted compacted layers down to 35 cm, reducing the 10-25 cm layer bulk densities (1.3 g/cm^3) of 15-20%, with a trend to higher yields (Bell et al., 1996). However, the number of experiments is limited, and there is a need for further studies to investigate deep tillage effects on soil moisture, bulk density and strength, as well as the crop yield of ripping soils in the long-term (Bell et al., 1996; Cotching et al., 2005).

2.4 Vertosols

With the beginning of the twentieth century, Vertosols or dark cracking clays as the tropics and sub-tropics clayey soil, attracted the attention of scientists and researchers (Harrison & Sivan, 1912; McKenzie, Abbott, & Higginson, 1983). The Latin name, "*vertere*", is the genesis of Vertosols name which means to turn or invert, confirming that these soils are descended from assets that are strongly affected by soil mass contraction and expansion or soil movement and soil materials turbation (Wilding, Smeck, & Hall, 1983, p. 91). In terms of soil homogeneity, Vertosols are considered the most homogeneous (Ahmad & Mermut, 1996).

Based on texture, Vertosols are grouped into *Light Vertosols* (35-55% clay) and *Heavy Vertosols* (56-80% clay) (Connolly et al., 1997, p. 1344). Also, *Light and Heavy Vertosols* soil types are classified as Brown and Grey Vertosols and Black and Grey Vertosols according to (Isbell, 1996) respectively, and both are ordered as Vertisols according to (Taxonomy, 1975) with general characteristics as 'Clay soils with shrink-swell properties that exhibit strong cracking when dry and having slickensides and/or lenticular structural aggregates at depth, medium Plant Available Water Capacity (PAWC)' for Light Vertosols and high PAWC for Heavy Vertosols (with >55% clay) (Connolly et al., 1997), sodic in many places (Ghosh et al., 2010), hard to cut, loosen, or forming furrows via tillage tools when it becomes so dry or moist (Møberg & Esu, 1991), with low penetration resistance (soil strength) in wet conditions (Antille, Bennett, et al., 2016; Bennett, Woodhouse, Keller, Jensen, & Antille, 2015; Hodgson

& Chan, 1984; Wong, Greene, Dalal, & Murphy, 2010), very prone to damage by farm machinery (Braunack & Johnston, 2014; Wild et al., 1992), fertile (Dudal & Eswaran, 1988), dominate the cotton industry (Hartmann et al., 1998; Wild et al., 1992) and also used for a range of cropping purposes (Connolly et al., 1997; Connolly et al., 2001), with inherent slow water infiltration when soil is swelling (moist) (Williams, 1983) however, it never stops (Hochman, Dalgliesh, & Bell, 2001).

Vertosols cover up to 4% of the tropic land area, which represents about 320 M ha (Dudal & Eswaran, 1988), and the majority of them are located between 45º N and 45º S (Graham & Southard, 1983; Harris, 1958; Knight, 1980). In Africa, Vertosols (heavy black clay soils) occupy about 35% of the world's Vertosols with about 109 M ha (Santanna, 1989), of which 43 M ha (14%) are in sub-Saharan Africa (Ayele, 2001). After Africa, Australia, with over 80 M ha or about 23% of the world's Vertosols (Figure 2-13), has the second largest Vertosols occurrence, most of which >70% are found in Queensland and NSW (Dalal, 1990; Dang et al., 2018; de Vetten, 2014; McGarity, 1975). This exceeds India's 73 M ha (21.65%), Sudan's 50 M ha (14%), and USA's 18 M ha (5.33%) (Ahmad & Mermut, 1996).

In Queensland, Vertosols represent one of the most common soils, accounting for about 50 M ha of the state's total land used for row and cereal crop production (Freebairn et al., 1986; Hulme et al., 1996; Martin & Cox, 1956). In south-western Queensland, Vertosols represent one of the most exploited soils for grain cultivation (Dang, Routley, et al., 2006). Weston et al. (1983) reported that Vertosols for grain farming in Queensland and northern NSW are about 2.5 M ha with an intention to add 4-6 M ha for grain production in Queensland alone.

Vertosols are distinguished by low to moderate organic matter and high clay content that can self-mulch according to water content percentage (Rincon-Florez, Carvalhais, Dang, & Schenk, 2016). Despite their presumed structural robustness and ability for `self-repair' with wetting and drying as a result to shrink-swell features (Hodgson & Chan, 1984), Vertosols are insufficient for structural degradation rehabilitation (Hartmann et al., 1998) and reinforce the permeability (Beckmann & Thompson, 1960) under intensive cultivation condition. Also, under compaction conditions, the ability of microbes to take up nutrients will reduce, and soil fertility will decline (Cookson, Murphy, & Roper, 2008).

Even though the shrinking and swelling feature of Vertosols uplifts an integrating of surface and subsurface materials, the nonstop shrinking and swelling helps to reduce microbial biomass on the soil surface (Blokhuis, Kooistra, & Wilding, 1990). Similarly, at two Queensland sites (Biloela and Jimbour), the lab tests of soil by Florez (2016) had showed that Vertosols' surfaces were lower in fauna biomass percentage compared to subsoils. Similarly, Dang, Dalal, Routley, Schwenke, and Daniells (2006) found that, sodicity, low nutrients and low microbial community abundance on the surface are the general properties of Vertosols.

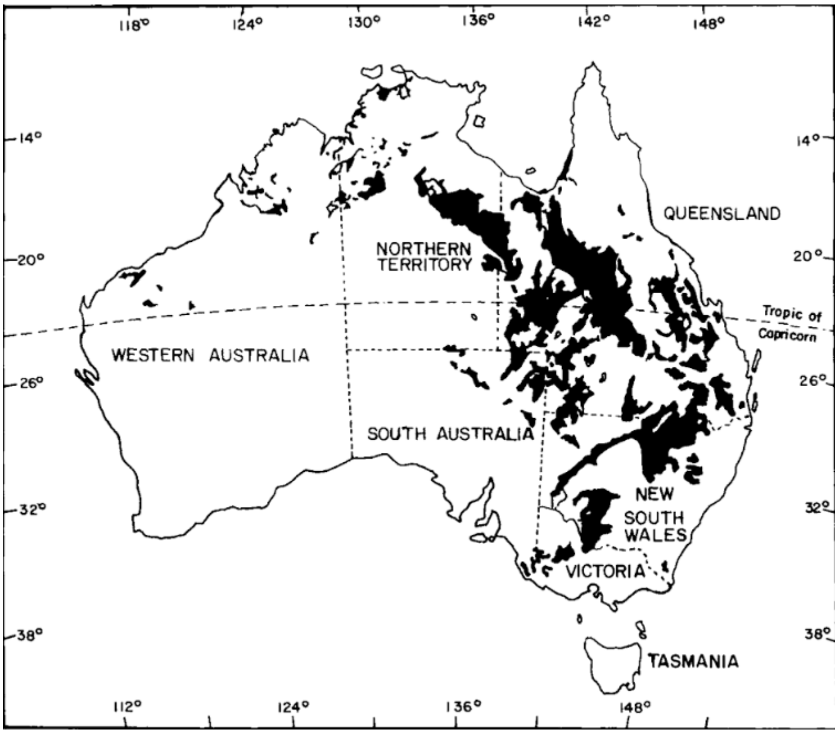

Figure 2-13: Distribution of Vertosols in Australia (Isbell and Committee, 1989 in Ahmad and Mermut (1996))

Besides the infiltration nature which is responsible for wetting subsoil profiles of most soil types, the cracking nature of Vertosols enhances the moistening of subsurface aggregates (Smith, Tongway, Tighe, & Reid, 2015) and allows organic matter to fall into deeper layers (Blokhuis et al., 1990). The soil tests showed that the percentage of soil organic carbon decreased from 2.1% to 1.6% and from 2.0% to 1.8% with increasing depth from 0 - 10 cm to 10 - 20 cm for the light (35-55% clay) and heavy (>55% clay) Vertosols respectively (Connolly et al., 1997). Regardless of soil textural class, the presence of organic matter helps to protect soil from compaction risk via traffic due to the improvement of soil structure (Soane, 1990) as well as drainage conditions (Dıaz-Zorita & Grosso, 2000; Kumar et al., 2009).

In the cultivated Vertosols found in south-east Queensland, large concentrations of exchangeable ammonium (NH_4^+) in quantities ranging from 200 kg N/ha to 270 kg N/ha have been found below 1 m depth (Hossain, Dalal, Waring, Strong, & Weston, 1996). This is considered a valuable reserve for crop growth if it is able to move into the root zone or if the roots of the crops are able to reach it (Page, Dalal, Menzies, & Strong, 2003). Deep ripping is one of the best approaches for achieving this.

Due to unique properties such as colour, texture as clay residues from rock weathering with minerals presence like smectite or 'smectite clay mineralogy', swelling and adhesion, cohesion and stickiness, very low infiltration and permeability when wet, shrinking, cracking to a depth of 500 mm or more (Eswaran, Kimble, & Cook, 1988), and hardness when dry, high chemical activity, high water adsorption, Vertosols have been recognized as difficult to manage (Ahmad & Mermut, 1996). Bennett, Woodhouse, et al. (2015) and Antille, Bennett, et al. (2016) stated that since Vertosols are characterised as fine textured with often extremely high clay content (>80%), cohesion is a dominant factor in governing soil strength, so only small increases in soil moisture result in a drastic reduction of soil strength and ease of compaction. Despite these difficulties, Vertosols are productive soils (Melaku et al., 2018) if managed properly (Bennett, Cattle, et al., 2015; Wubie, 2015). Finally, to establish sustainable crop production without negatively impacting the health of Vertosols, further studies in agricultural management are needed (Florez, 2016).

As we have seen, clay soils are among the most exploited for the grain production, especially wheat and sorghum. The next sections will address wheat and sorghum as they were the planted crops in our study.

2.5 Wheat

Wheat is important global crop (Röder et al., 1998) belonging to *Gramineae* family (Wang et al., 2002) with a root elongation ability ranging between 1.5 m and 2 m in depth if the right conditions exist (Anderson, Fillery, Dunin, Dolling, & Asseng, 1998; Kirkegaard & Lilley, 2007; Rasmussen, Dresbøll, & Thorup-Kristensen, 2015; Van Noordwijk et al., 1991). It is a temperate (Mediterranean) and tropical climate crop, as winters are usually moist and mild and summers are warm to hot, sunny, and long and dry with relatively scattered rainfall during autumn and spring (Röder et al., 1998; Simmonds, 1989; Wang et al., 2002). In Australia, wheat cultivation settles within a belt that receives an average 300 mm of rainfall during the period May to October (Simmonds, 1989). Therefore, the incidence of rainfall is considered the main factor affecting the variability of wheat production.

Wheat growth is completely dependent upon winter rains in Western Australia except in the southern areas, while in western Victoria and southern NSW, high yields are related to high spring rainfall (Simmonds, 1989). In the northern NSW and southern Queensland rainfed cereal region, summer rainfall is predominant, so winter wheat growing depends mainly on the soil's stored water (Perry, 1992). In southern Queensland wheat-growing regions, soil type is classified as heavy and deep clay soils (Simmonds, 1989). Thus, improving soil physical properties by increasing its capacity to absorb and store rain-water is an essential factor for increasing wheat production.

2.6 Sorghum

In most developing countries, sorghum plays a major role as food and feed (Buah & Mwinkaara, 2009). Recently, it has been employed as an energy source for integrated bio-refineries in developed countries (O'Hara et al., 2013). Komolong et al. (2002) also stressed the necessity of introducing sorghum cultivation as a summer crop in agricultural rotation to help arable soils combat endemic diseases as well as wind erosion and runoff.

It is one of the dryland, tropical, subtropical, and temperate regions' water-efficient cultivated crops (Almodares, Taheri, & Safavi, 2008), belongs to *Gramineae* family (Wang et al., 2002), has high yield of biomass (Almodares, Sepahi, Dalilitajary, & Gavami, 1994; Gardner, Maranville, & Paparozzi, 1994), and characteristics to resist soil drought (Staggenborg, Dhuyvetter, & Gordon, 2008; Tesso, Claflin, & Tuinstra, 2005), salinity (Netondo, Onyango, & Beck, 2004), and low fertility (Van Oosterom, Carberry, & Muchow, 2001). MR-Buster is Australia’s benchmark sorghum hybrid with grain medium maturity for all planting situations (Wood, Tan, Mamun, & Sutton, 2006). The environment, row spacing, plant density (Conley, Stevens, & Dunn, 2005; Lafarge, Broad, & Hammer, 2002), fertiliser rate (Buah & Mwinkaara, 2009; Moosavi et al., 2013) and fertiliser time (Melaku et al., 2018; Strong, 1986) have a significant effect on sorghum yield.

As a result of continuous and dense cereal cropping, N is the first element that suffers depletion, either because of direct consumption by plants or via emission to the atmosphere as N_2O due to the soil compaction. Therefore, this deficiency must be compensated using N fertilisers.

2.7 Nitrogen-based fertiliser

In most cultivated soils, organic matter is a major indirect source of nutrients like N, P, S, and K that are released through bacterial and other metabolic processes (Cuttle et al., 2003). Thus, soils with high organic matter are considered low-cost and profitable since its productivity that does not require massive quantities of expensive NPK fertiliser. It also contributes to maintaining a suitable soil composition for crop growth, in cations retention, and in creating conditions for micro-elements' formation (such as Cu, Zn, Mn, and Mg) (Dalal & Mayer, 1986b). During the growing season, the soil nutrients are either absorbed or lost through plants or leaching. To maintain the nutrients in consistent and positive balance, nutrient compensation by chemical fertilisers and manures through fertilisation, is required (Buah & Mwinkaara, 2009; Melaku et al., 2018).

In continuous crop rotation systems and as a result of nutrient depletion during the growing season, N is often the first nutrient depleted by plants (Breland & Hansen, 1996; Hansen & Henriksen, 1981; Probert, Carberry, et al., 1998). Also, in compacted soil, N is more likely to be lost as N_2O emissions. Numerous studies, e.g. Ball, Parker, and Scott (1999), Dobbie and Smith (2003), Vermeulen and Mosquera (2009), Milne et al. (2011), and Powlson et al. (2012) reported that poor aeration and water-filled pore space raises soil temperature and then increases N_2O emissions. In waterlogged soil, the amount of accessible N via plant roots can also be reduced significantly due to microbial processes (Boone & Veen, 1994). Similarly, in farms under tillage systems, N application is necessary as tilled soil creates favourable metabolic environments for soil microorganisms via aeration, and thereby accelerates soil organic matter oxidation (Dalal, 1992; Doran & Smith, 1987). Consequently, the N availability in farm soil is considered a major factor in increasing profitability by increasing crop productivity. Therefore, farm soil fertility should be one of the top farm management priorities (Probert, Dimes, et al., 1998). Moreover, if the soil is not fertilised with new nutrients, it is highly likely that the quantity, quality and grain protein content of the subsequent crop will decrease (Probert, Carberry, et al., 1998).

N fertiliser is important because it improves rooting depth, nutrient uptake and availability, and leaf area which, in turn, lead to quantitatively and qualitatively optimized grain yield as well as net benefits (Khosla, Alley, & Davis, 2000; Lehmann, Feilner, Gebauer, & Zech, 1999; Ogunlela & Okoh, 1989; Workayehu, 2000; Yamoah, Bationo, Shapiro, & Koala, 2002). Several studies (Haberle, Svoboda, & Krejcova, 2006; Kristensen & Thorup-Kristensen, 2004; Thorup-Kristensen, Cortasa, & Loges, 2009), have confirmed the linear correlation between root growth and elongation with N availability in soil layers. While Mosier, Syers, and Freney (2004) and Zhao, Reddy, Kakani, and Reddy (2005) had another view that N is an essential element in the composition of nucleic acid (biomolecules), amino acid, and some organic acids which play an important role in plant growth and development; thus, reduce the probability of lower yields after production.

Most applied fertiliser research in the grain farming zone of southern Queensland has concluded that N deficiency is a major cause of suboptimal economic yields (Strong, 1986). Continuous cereal cropping post-tillage in southern Queensland soils has led to a marked reduction in grain yields (Dalal, Strong, Weston, & Gaffney, 1991) due to soil structure degradation (Cook, So, & Dalal, 1992; Dalal & Mayer, 1986a) and plant-ready N deficiency as a result of reduced soil organic matter (Dalal & Mayer, 1986a; Dalal et al., 1995). Annually, the total N (0-100 cm) of Queensland soil devoted to cereals cultivation decreases by approximately 25±2 kg/ha due to crop absorption and NO_3-N leaching (Dalal, 1992). Thus, the annual cereal production plans which include N fertiliser application, will conserve soil fertility, maximise grains yield, and enhance crop systems sustainability (Probert, Carberry, et al., 1998).

Given the N fertility of soil, most of the world's farmers apply N fertiliser in rates ranging between 45 kg N/ha and 224 kg N/ha for cereal crops (Zhao et al., 2005). Gourley and Ridley (2005) have stated that the annual amount of applied N to Australian cereal crops ranges from 150 kg/ha to 250 kg/ha. From Chamen et al. (2015), the N rate of 200 kg per hectare is a is a common rate approved by most of British farmers during cereal cropping practice. Strong (1981) mentioned that, on some soils, to produce grain yield optimally, more than 200 kg/ha of N fertiliser is required. However, low crop yield due to N fertiliser application at minimum rates, is considered less dangerous than excessive application which may lead to groundwater contamination which negatively impacts future human and animal health (Jaynes, Colvin, Karlen, Cambardella, & Meek, 2001).

In the 2001-02 season, 178 kg/ha of N (as 350 kg/ha of urea) was applied to maize sowing on a grey Vertosol soil type in Dalby, southern Queensland (Peake, Robertson, & Bidstrup, 2008). Recently, on Red Ferrosol soil in Toowoomba, Hussein (2018) concluded that adding urea (46% N) after sorghum and wheat sowing, at a rate of 140 (as 304 kg/ha of urea) and 110 (as 239 kg/ha of urea), respectively were the optimum economic rates compared to other quantities. In Moeller et al. (2007), wheat experiments conducted in 1999-2000 on a Vertosols soil type in Tel Hadya, north-western Syria, the application of 100 kg N/ha (as 197 kg/ha of urea) significantly increased grain yield and total dry biomass compared with the unfertilised treatment. On Darling Downs (Toowoomba region) black Vertosols, 69 kg N/ha (as urea before sowing at 4-5 cm depth) was the highest chosen rate in Marley and Littler (1989) 1968-1979 and Dalal (1992) 1981-1990 long-term experiments conducted to investigate the effect of tined tillage, zero tillage and N rate on wheat and barley growth and yield.

N presence is considered necessary through all stages of plant growth (Mosier et al., 2004) and is a determinant of increasing crop yield (Moosavi et al., 2013; Zhao et al., 2005). In Europe and Great Britain, to increase fertilisation efficiency, N fertiliser is applied after sowing at a specific phase of plant growth stages to ensure N availability at a sufficient rate (Strong, 1986). However, in the southern Queensland irrigation region, it is customary to apply N fertiliser to cereal crops in the three months before sowing (Strong, 1986). This application could be inefficient, creating the possibility losing most of N if the soil is saturated (waterlogged), (Craswell, 1978) or the N may become ineffective (immobilized) during decomposition of previous crop residues (Freney & Galbally, 1982). Furthermore, Littler (1963) and Cooper (1974) concluded that, for crops under dry conditions, N application elicited no response.

Generally, the winter of southern Queensland region is characterised as low rainfall, (Nuttall, Davies, Armstrong, & Peoples, 2008) thus N application after sowing may have some positive effects on rain-fed crop yield through: 1) N fertiliser added when the young plant in urgent need, 2) after seedling emergence, according to plant density, a better assessment of fertiliser amount to be added will be possible, 3) for some crops which are planted in wet seasons (wet soil), fertilisation after sowing is the only solution or with the minimum tillage system (Strong, 1986). Similarly, in the southern Queensland region, Littler (1963) and Cooper (1974) observed that good rain after N fertiliser application to cereal crops during the early crop growth stage, gives a good reaction.

In Strong (1986) experiment, N fertiliser as a urea solution was applied pre-sowing and after 60, 81 and 103 days of wheat seedling emergence which coincided with tillering (1, 2, 3, 4 and 5), booting (10), and flowering (10.5) of cereals growth stages respectively (Large, 1954). The application of N fertiliser during the tillering stages was usually more effective in raising yield than after tillering or between the tillering and flowering stages. The tillering stages seem to be the preferred time to add urea after sowing since it enhances crop tillering which, in turn, leads to increases in grain yield (Strong, 1986).

During Almodares, Jafarinia, and Hadi (2009) experiment, urea was added to the furrows after sorghum sowing and when the plant had three to four leaves (Stage 2 of the ten stages of sorghum development) (Vanderlip, 1972). Adding N fertiliser after 35 days of sowing or planting was one of Buah and Mwinkaara (2009) fertilisation strategies. They justified that, at this time the plant would be growing rapidly, and N would be necessary.

Across seasons and sites, cereal crops differ in their response to N fertiliser application rates owing to farm management, variation in plant genotypic and cultivar, soil conditions and type, and climate conditions (Van Oosterom, Carberry, & Muchow, 2001). Numerous studies have shown that grain and biomass crop yield productivity increase with the application of N fertilisers (Aflakpui, Anchirinah, & Asumadu, 2005; Buah, Maranville, Traore, & BrameI-Cox, 1998; Muchow, 1990; Workayehu, 2000). Buah and Mwinkaara (2009) observed that N fertilised sorghum flowered five days earlier than unfertilised sorghum.

The sorghum grain yield showed a statistically significant increase ($p < 0.05$) from 1189 kg/ha to 3341 kg/ha when the rate of N increased from 0 kg/ha to a one time application of 87 kg/ha as urea applied after planting (at knee height stage) (Melaku et al., 2018). Moreover, compared to the N fertilised plots, corn and sorghum yield decreased by 41% and 19%, respectively, for non-nitrogenized plots (Mengel, Kirkby, Kosegarten, & Appel, 2011). As well, Mahmud, Ahmad, and Ayub (2003) observed that increased N application (as urea) from 0 kg/ha to 100 kg/ha led to a significant increase from 23400 kg/ha to 38800 kg/ha for sorghum green fodder yield.

Compared with no N fertiliser treatment (control), increasing the N fertiliser rate from 40 kg N/ha to 80 kg N/ha and then to 120 kg N/ha resulted in 5%, 16% and 23% (respectively) increase in biomass yield at flowering (Buah & Mwinkaara, 2009). Similarly, sorghum dry biomass was significantly higher (10897 kg/ha) with a onetime application of 87 kg N/ha as urea applied after planting (at knee height stage) as compared to 0 kg N/ha which was 3696 kg/ha (Melaku et al., 2018). Additionally, Mahmud et al. (2003) observed that increasing N application (as urea) from 0 kg/ha to 100 kg/ha led to a significant increase in sorghum dry matter from 8100 kg/ha to 13240 kg/ha. Furthermore, sweet sorghum biomass at dough stage increased significantly from 55.50 t/ha to 59.10 t/ha to 62.10 t/ha and then to 64.80 t/ha by increasing N fertiliser level from 50 Kg/ha to 100 Kg/ha to Kg/ha 150 and then to 200 Kg/ha respectively (Almodares et al., 2009) which agrees with Johnston, Trust, and Fellow (2000) findings.

In addition to the crop yield and dry biomass, research findings differed in the efficiency of the harvest index as an indicator of fertilisation evaluation. Increased N application from 0 kg/ha to 225 kg/ha led to a significant ($p < 0.05$) increase in sorghum grain yield from 500.4 kg/ha to 1606.25 kg/ha and dry biomass from 5516.67 kg/ha to 7970.42 kg/ha. The grain harvest index (HI) was significantly influenced by increasing N fertiliser, so that 0 kg/ha application produced the lowest grain HI of 10.99% and the highest HI of 20.03% at 225 kg/ha (Moosavi et al., 2013). However, N rates did not affect the sorghum HI. Nonetheless, increased N application from 40 kg/ha to 80 kg/ha and then to 120 kg/ha led to a significant ($p < 0.05$) increase in sorghum grain yield from 2137 kg/ha to 2198 kg/ha and then to 2223 kg/ha, respectively and biomass yield at flowering from 4817 kg/ha to 5298 kg/ha and then to 5627 kg/ha, respectively compared with farmers' practice (0 kg N/ha) which was 1536 kg/ha and 4573 kg/ha for grain yield and biomass yield respectively (Buah & Mwinkaara, 2009).

Due to the continuous increase in the N fertiliser prices and seasonal use, most worldwide fertiliser research aims are centred on finding the highest economic returns from the smallest amount of N fertiliser (Muchow, 1998; Sheehy et al., 1998). Using N fertiliser has a positive economic impact on sorghum yield (Buah & Mwinkaara, 2009). In clay soils, the gross margin (net benefit) tended to decline at a quicker rate than yield with an increasing cropping period due to the rapid decline in soil fertility level, and increasing N fertiliser costs related to increased application (Connolly et al., 2001).

As mentioned above, fertilisation has a good economic return because it increases crop production by nearly half if it is applied in an effective amount and at the correct time. Despite the abundance of research dealing with fertilisation effects on crop agronomy, the effect of twinning fertilisation with deep tillage on the crop productivity in clay soils has not been addressed satisfactorily by researchers. Deep tillage experiments require more time, effort and financial resources, and farmers' fear experimentation with it on their farms. This has had a significant impact on the knowledge base.

It is clear that fertilisation compensates the depletion of soil nutrients as a result of regular, intensive or continuous cultivation and therefore, positively impacts productivity and profit. However, productivity and profit are negatively impacted when soil suffers from compaction (due to reasons that will be explained in the next section).

2.8 Soil compaction

In the early 20th Century, compaction was recognized as a key factor in reducing crop yield due to the widespread use of large vehicles in agricultural production (Raper & Bergtold, 2007). Nearly 25 years ago, many soil scientists, including Soane and Van Ouwerkerk (1995), pleaded for a uniting of efforts to study compaction causes, mitigating methods, costs and profits. In recent years, soil compaction has received a great deal of interest due to: 1) the tendency of the agricultural sector to mechanize most of agricultural operations with bulky and wider equipment (Ansorge & Godwin, 2007; Chamen et al., 2015) and 2) international recognition of the serious and growing threat to the sustainability of global food security (Jones et al., 2003; Nawaz et al., 2013). Compaction poses a critical threat affecting the common pillars of sustainable agriculture: machines, soils, plants and climate (Soane & Van Ouwerkerk, 1994), making it a concern for most of the world's farmers (Harrison & Licsko, 1989) and the greatest threat to agricultural production (Schjønning, Heckrath, & Christensen, 2009). Compacted hectares are estimated to be around 68 million worldwide (Nawaz et al., 2013).

SSSA (1997) cited in Sidhu and Duiker (2006, p. 1257) and Nawaz et al. (2013, p. 292), defined compaction as “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby, increasing the bulk density”. Basically, compaction is the alteration in soil volume (de Lima et al., 2017; Horn, Way, & Rostek, 2003; O'sullivan, Henshall, & Dickson, 1999). It is a process of increasing unsaturated soil bulk density either for external or internal reasons, driving the deterioration of the soil’s physical structure and is called consolidation in saturated soil (Farzaneh, Almassi, Sadeghi, & Minaei, 2012).

Bulk density and penetration resistance (cone index) are soil compaction inference indices (Hamza, Riethmuller, & Anderson, 2013; Martínez et al., 2016; Raper, Reeves, Burt, & Torbert, 1994; Šařec & Žemličková, 2016; Voorhees, 1983). Therefore, most of crop yields prediction models, such as SIMWASER (Stenitzer & Murer, 2003), derive compaction from bulk density or penetration resistance (Lipiec, Arvidsson, & Murer, 2003).

Soil bulk density is the simplest physical function used for compaction detection by determining the change in soil volume. However, it is not recommended for measuring traffic impact on different soils as each soil has its own bulk density range (Håkansson & Lipiec, 2000; Keller & Håkansson, 2010; O'sullivan, Robertson, & Henshall, 1999). Soil penetration resistance is a well-known physical indicator used to identify soil compaction by trafficking and compacted level (O'sullivan, Dickson, & Campbell, 1987; Reeder, Wood, & Finck, 1993) and detect the critical root zone condition which hinders plant root growth and elongation (de Lima, da Silva, Da Silva, Leão, & Mosaddeghi, 2016; Keller et al., 2015; Silva, Kay, & Perfect, 1994). Soil penetration resistance value, however, varies depending on the state of both soil bulk density and moisture content (Ekwue & Stone, 1995; Vaz, Manieri, & de Maria, 2013; Vaz, Manieri, De Maria, & Tuller, 2011). Hence and whenever possible, soil penetration resistance measurements are recommended after irrigation or a heavy precipitation event when the soil moisture content will be highly consistent throughout the soil profile (Chen, Cavers, Tessier, Monero, & Lobb, 2005; Materechera & Mloza-Banda, 1997). Furthermore, to obtain a representative measure of soil strength, Standard EP542 - ASABE (1999) recommends taking at least 20 cone penetrometer measurements near the field capacity (one or two days after a rain or irrigation (Kirkham, 2014)).

Soil bulk density and the cone index are commonly used to measure changes in soil porosity (distribution of porosity) which have an instant effect on the degree of compactness related to field traffic and to evaluate equipment efficiency when removing or reducing post-traffic compaction (de Lima et al., 2017; Koolen & Kuipers, 1983; Rivenshield & Bassuk, 2007).

Generally, compaction occurs in all soil textures, but the degree of compactness increases with the increasing proportion of clay (Imhoff, Da Silva, & Fallow, 2004; Manuwa, Adesina, & Olajolo, 2011; Pagliai, Marsili, Servadio, Vignozzi, & Pellegrini, 2003; Stenitzer & Murer, 2003). Many researchers, such as Håkansson (1985), Etana and Håkansson (1994), and Alakukku and Elonen (1995), have conducted field trials resulting in data showing that compaction may exceed a depth of 0.5 m in clay soils subjected to heavy machinery locomotion with loads of up to 10 tonnes.

Due to the nature of conditions, human activities or both, top and subsoil compaction can occur. For a major portion of total cultivated lands, compaction affects the upper soil layer (Nawaz et al., 2013) as a result of machines frequency passing over soil (Botta, Jorajuria, Rosatto, & Ferrero, 2006; Sakai, Nordfjell, Suadicani, Talbot, & Bøllehuus, 2008). In very few cases compaction can be useful. This is when its degree is quite slight in lighter and coarse-to-touch soils (sandy soil) (Bouwman & Arts, 2000). But, in most cases, compaction is considered a limiting factor for seed emergence and root growth (Botta et al., 2006; Sakai et al., 2008). Compacted topsoil can be repaired with biological tillage (Chen & Weil, 2010; Davies et al., 2019) or surface tillage (ploughing via chisel, tandem disk, moldboard) for several years, (Chamen, 2015; Schäfer-Landefeld, Brandhuber, Fenner, Koch, & Stockfisch, 2004) but still topsoil may not always return to its native state (Gameda, Raghavan, Theriault, & McKyes, 1983; Reeder et al., 1993; Voorhees, 1983). By contrast, subsoil compaction is considered a very serious problem because it is complex (Froehlich, Miles, & Robbins, 1985), expensive (Payne, 2008), hard to mitigate (Thakur & Kumar, 1999), has lasting persistent negative effects on crop yields and growth (Chamen et al., 2015), as well as soil structure (Berisso et al., 2012; Chan, 1982; McKenzie et al., 1983; Wild et al., 1992). Thus, Hamza and Anderson (2008) concluded that subsoil compaction is one of the major problems facing modern intensive agriculture. Accordingly, it has been recognized by the European Union as a serious threat targeting the soil entity and thus plant growth (Jones et al., 2003).

In their review of subsoil compaction prevention methods, Alakukku et al. (2003) divided subsoil compacted due to traffic into two featured layers: the pan layer and unloosened subsoil. They indicated that a pan layer is formed immediately below the yearly cultivated layer via implements or wheels, or jointly. It is a thin layer and can be removed by changing the tillage depth, so it may not require regular subsoiling compared to the unloosened subsoil layer. However, soils under conventional tillage (to approximately 10 cm depth) are less compact than those under no-tillage systems (Dalal, 1992; Hamblin, 1987; Unger & McCalla, 1980).

Farming land compaction causes increased soil bulk density (Blake & Hartge, 1986; Donald, 1987; Freitag, 1971), increased soil strength impeding root growth (Hulme, 1987; Whitmore, Whalley, Bird, Watts, & Gregory, 2011), reduced soil porosity, air permeability and water infiltration rates (Chamen, 2011; da Silva & Kay, 1996; Laker, 2001; Venezia, Del Puglia, & Lo Cascio, 1995), hydraulic conductivity (Alakukku, 1996; Freitag, 1971; Kirkham, 1947; Nau, 1987), fewer large pores (DeJong-Hughes, Moncrief, Voorhees, & Swan, 2001; Gupta et al., 1989; Hamza & Anderson, 2003; Hamza et al., 2011), altered manner of aggregation and cracking (McGarry, 1990), and soil erosion due to increased runoff during rain (Arvidsson & Keller, 2004). In addition, on compacted soil, rainfall water more readily by evaporates as it moves very slowly through the compacted soil layers (Connolly et al., 2001). In addition, compaction can result in less absorption of accessible nutrients due to root dwarfism (Miransari, Bahrami, Rejali, & Malakouti, 2009; Wolkowski, 1990). Also, soil fertility and crop sustainability can decline as a result of microbial community inactivity because soil compaction minimises air porosity (Ceja-Navarro et al., 2010). Further, the microbes' ability to take up nutrients will significantly decrease with an increasing compactness rate, and this may get worse in clayey soils (Cookson et al., 2008). It is generally accepted that the implement points and tractor wheels will be subjected to rapid abrasion due to the increasing strength of compacted soil (Fielke, Riley, Slattery, & Fitzpatrick, 1993; Owsiak, 1999; Richardson, 1967).

Moreover, worldwide, in cereal cultivation zones with temperate, high rainfall and/or poor drainage, waterlogging is one of the results of compaction which represents a significant limitation on world and Australian grain production (Manik et al., 2019; Melaku et al., 2018) (Acuña, Dean, & Riffkin, 2011). Hodgson (1986) stated that waterlogging is considered one of the Vertosols' subsoil compaction results in cotton fields. Waterlogging is defined as the decreasing of soil pore spaces' oxygen diffusion capacity around the root zone (Christianson, Llewellyn, Dennis, & Wilson, 2010; Drew & Sisworo, 1977; Jaiswal & Srivastava, 2018; Lee et al., 2007). The O_2 depletion during waterlogging impedes a plant's ability to take up nutrients (Setter & Belford, 1990) due to the reduction of energy available to roots (Armstrong, Justin, Beckett, & Lythe, 1991). The Australian grains industry suffers an annual loss about AUD180 million $year^{-1}$ due to waterlogging (Pang, Zhou, Mendham, & Shabala, 2004). In the Australia wheat growing zone, a wet year (year with high rainfall (>500 mm)), can produce waterlogging that causes 40-50% reduction in yield (Zhou, 2010) and, thus, a financial loss of about AUD100 million (Zhang, Turner, & Poole, 2004). Globally, the arable land ratios experiencing waterlogging are 16% in the United States, 10% in Russia, India, Pakistan, Bangladesh and China (Yaduvanshi, Setter, Sharma, Singh, & Kulshreshtha, 2012).

Based on statements of Czyż (2004) that the importance of moderate soil compaction lies in increasing the root-to-soil contact, soil compaction is important to the environment, plants and sustainable food production (Dobbie, Bruneau, & Towers, 2011) cited in (Chamen et al., 2015, p. 11). However, there are many reasons making the acceptable compaction to develop into a critical level that hinders water and plant roots movement include the naturalistic soil displacement, the immersion of soil with weak construction with water due to heavy rain, the passage of heavy agricultural vehicles tires on field soil, and soil cultivate via tillage equipment at one depth seasonally or annually without changing (Koolen & Kuipers, 1983). Raper and Bergtold (2007) have identified two reasons for the occurrence of compaction. First, vehicle traffic which is easy to observe from reduced crop yield due tractors or implements creating ruts as a result of increased waterlogging soil surface. This is due to reduced infiltration causing increased soil bulk density. Second, hardpans which are difficult to diagnose and prevent root penetration and negatively impact yield. They attributed the creation of hardpans to two main causes. First, the continual use of the same ploughing operation depth over many seasons. Second, natural soil displacement in which small particles overlap with large particles, partially or totally preventing porosity (Raper & Bergtold, 2007). Climate change and food demands have more recently been identified as environmental and social drivers that may influence soil compaction (Chamen et al., 2015).

In general, the compaction rate is directly proportional to the vertical load pressure on its surface. Thus, in soil profile, soil weight causes compaction and accordingly, bulk density and compaction increase as soil depth increases (Hartge, 1988; Lowery & Schuler, 1988). This confirms soil compaction to be natural in virgin soils subsoil layers (Hamza et al., 2011, 2013), however in an agricultural setting, it is the departure from this soil bulk density reference that constitutes soil compaction. Farzaneh et al. (2012) observed that there is a significant relationship between soil depth and its bulk density in different levels of moisture (8%, 13%, 18% and 23%). The effect of moisture on bulk density in ploughed soil was seen to be significant. At every depth, soil bulk density increases with soil moisture and its highest level corresponds with moisture of 23%. They found that lubrication between soil particles improves and cohesion between particles decreases, thus enabling smaller particles to move easily and fill empty spaces between bigger particles and increasing bulk density. This finding is in line with Proctor (1933) results.

Compaction may also mitigate naturally. In cold zones, as result of increasing soil water volume upon freezing, soil compaction can be naturally alleviated through soil aggregate disruption (Bullock, Nelson, & Kemper, 1988; Kay, Grant, & Groenevelt, 1985; Marshall, Holmes, & Rose, 1996). Also, deep penetration of crops roots to (0.15 - 0.50 m) through compacted soils works as ‘biological tillage’ (Chen & Weil, 2010), ‘biological drilling’ (Davies et al., 2019), or bio-drilling (Cresswell & Kirkegaard, 1995) that causes soil fragment by deeply penetrating tap roots which then modified subsoils (Chen & Weil, 2010; McCallum et al., 2004; Rosolem, Foloni, & Tiritan, 2002; Yunusa & Newton, 2003). Such biological tillage may be especially functional in no till cultivation system (Stirzaker & White, 1995; Williams & Weil, 2004), when soil pores are smaller than root diameters (Bengough & Mullins, 1990; Clark, Whalley, & Barraclough, 2003) for crop species with deeper penetrating tap roots

(Ishaq, Ibrahim, Hassan, Saeed, & Lal, 2001), and greater root diameter (Materechera, Dexter, & Alston, 1991; Misra, Dexter, & Alston, 1986). Moreover, the shrinking and swelling feature induced by the drying-wetting cycles of some clayey soils (Vertosols) enables soil layers to mix and subsoil compaction to be ameliorated (Blokhuis et al., 1990; Hodgson & Chan, 1984). However, the extent of repair is insufficient for machine induced (traffic) structural degradation rehabilitation (Bennett, 2016; Hartmann et al., 1998; McHugh, Tullberg, & Freebairn, 2009; Pillai-McGarry & Collis-George, 1990).

In Queensland, for cereal land under no-till and conventional farming systems, soil compaction has been occurring naturally as a result of high annual rainfall (>500 mm) in recent years (Rincon-Florez, Dang, Crawford, Schenk, & Carvalhais, 2016). Furthermore, with regard to soil surface, the raindrop effect on tilled and no-till soil induces a breakdown of its aggregates and crusting respectively (Bridge & Bell, 1994; Loch, 1994; Odey, 2018; Tullberg, Ziebarth, & Li, 2001). Crusting is a fluffy compact layer formed on the bare soil surface roughly 0.762 cm (Duley, 1940) and is considered a main limitation of infiltration (Brakensiek & Rawls, 1983).

Compared to nature, human intervention has a greater role in the development of problematic compaction. Compaction by agricultural field vehicles is considered one of the biggest problems associated with soil landscape degradation (Alakukku et al., 2003; de Lima et al., 2017; Florez, 2016; Lhotský, Beran, Paris, & Valigurská, 1991). Some think that heavy machinery could cause more compaction than the traditional tractors. Many experiments' results have concluded that, by increasing the number of passes or having small soil surface contact points, the lighter tractors may have the effect as heavier machines (Botta et al., 2006; Jorajuria, Draghi, & Aragon, 1997; Voorhees, Nelson, & Randall, 1986).

The effect of the tyre traffic on maize yield was studied by Canarache et al. (1984) in a Romania farm. They concluded that a 1 g/cm^3 increase in soil bulk density was due to vehicle traffic leading to a decline in corn yield by an average of 18% as a result of increasing soil resistance against root growth and elongation. Also, Raghavan, McKyes, Baxter, and Gendron (1979) noticed a 40% to 50% reduction in corn yield when an average increase in clay soil dry bulk density values for 0-20 cm depths rose from 0.89 g/cm^3 to 1.12 g/cm^3. They also found an average decrease in root density from 5.7 mg/g to less than 2 mg/g when the amount of tractor traffic increased from 1 to 5 to 10 and then to 15 simultaneously with increasing tyre contact pressure from 31 kPa to 41 kPa and then to 62 kPa (0.32 kg/cm^2 to 0.42 kg/cm^2 and then to 0.63 kg/cm^2) compared with the control (zero traffic).

In large holdings, most growers tend to use wide equipment (10-20 m in width) to increase operation productivity, and then face increasing food demand (Berisso et al., 2012), fuel prices and labour costs (Chamen et al., 2015). In farms with clay soils, the use of bulky tillage equipment may result in these soils becoming poor in drainage and poor in root growth (Chen et al., 2005). In addition, long-term continuous ploughing of clay soils will result in reduced hydraulic conductivities of the soil surface (0-10 cm) or below surface (10-30 cm), reducing crop production as a result of reducing rainfall infiltration, soil water storage and increasing runoff and erosion (Connolly et al., 1997). Put simply, soil with high clay content and poor drainage, soil compaction considers the biggest challenge that faces its managing (Chen et al., 2005).

For a long time, intensive tillage regimes and trafficking with over-sized and heavy machinery were part of Queensland farming systems' features producing degradation in soil structure, permeability, water retention and organic matter quantity and availability as a result of soil compaction (Connolly et al., 2001; McGarry, 1990). Ploughing of heavy-textured soils (with high clay content) for longer periods will lead to exponential decreases in hydraulic conductivity, macroporosity (pores > 0.3 mm in diameter), and the water-holding properties of soil below the cultivated layer (10-60 cm), while the loosening effect of tillage is somewhat advantageous for light-textured soils (18% clay) (Connolly et al., 1997; Connolly et al., 2001). Large soil pores or macroporosity are similar to the human arteries in their work, moving water, gases and nutrients to different soil layers. Thus, decreasing poor numbers due to compaction means a deterioration in soil health.

Soil ploughing with heavy machinery creates immediate compaction, increases soil bulk density and strength, reduces hydraulic conductivity and porosity of the layers below the ploughed layer (10-60 cm) (Connolly et al., 1997; Connolly et al., 2001; Gupta et al., 1989; McGarry, 1990), while the soil surface's (cultivated layer) structure will be highly likely to deteriorate (Freebairn, Rowland, Wockner, Hamilton, &

Woodruff, 1988), and the organic matter and fertility decline (Clarke & Marshall, 1947; Dalal & Mayer, 1986a) during high rainfall and cropping, respectively.

Random Traffic Farming (RTF) creates soil with high bulk density and strength, limiting porosity further, causing soil to compact (Tullberg, 2000). Such compaction is estimated to be 4 M ha, 33 M ha, 10 M ha, and 18 M ha in Australia, Europe, Asia, and Africa respectively (Flowers & Lal, 1998; Hamza & Anderson, 2003; Nawaz et al., 2013; Shahrayini, Fallah, Shabanpour, Ebrahimi, & Saadat, 2018). Plus to bulky machinery, the intensive and continue of tillage practice and cropping, overgrazing, and incorrect soil management, all are reasons causing soil to compact (Hamza & Anderson, 2005). Finally, compaction will affect the farm economy through reduced crop yield and increased total cost through an increasing number of required agricultural operations.

Subsoiling compacted soil (Chamen et al., 2015; Chen et al., 2005) with placing of inorganic amendment (e.g. gypsum or lime) or organic amendment (e.g. manures, compost) in sodic, acidic, saline, or non-fertile soils (Crabtree, 1989; Davies, Gazey, & Gartner, 2008; Henry et al., 2018; Matosic, Birkás, Vukadinovic, Kisic, & Bogunovic, 2018; McFarlane & Cox, 1992), minimizing or changing the timing of equipment traffic or livestock grazing (Chamen et al., 2015), low ground pressure of tractor tyres, tracked vehicles, and tool contact points on/in soil (Ansorge & Godwin, 2008; Blackwell, Webb, Lemon, & Riethmuller, 2003; Chen et al., 2005; Stranks, 2006), and combinations of two or more of the above adopted approaches (Al-Adawi & Reeder, 1996; Reeder et al., 1993; Threadgill, 1982), represent the dominant strategies used to alleviate or avoid soil compaction. Before going into deep tillage, we must first touch on the tillage systems used in Australia.

2.9 Australian soil tillage systems

Tillage is the mechanical manipulation of soil to increase crop production (ASAE, 1993; Boydaş & Turgut, 2007). Hill (1990) stated that soil physical and hydraulic properties can be affected by tillage operation and thus it has a direct impact on crop growth and production. In addition to physical properties, tillage has a direct effect on the chemical and biological properties, and consequently an indirect effect on the living organisms' activity and reproduction (Kladivko, 2001). In Australia, conventional, conservation, zero, and deep tillage are the common tillage systems (Hussein, 2018).

Conventional tillage is a traditional practice for preparing a seedbed and producing a given crop in a field (ASAE, 1993; Reeder, 2000). It usually involves operations of seedbed preparation such as primary and secondary tillage with harrowing operations (Schuller, Walling, Sepúlveda, Castillo, & Pino, 2007). It controls weeds and flips most of the soil surface, and it leaves the soils without residue for long periods which are likely to leave bare soil subject to rainfall and wind erosion (Martínez, Fuentes, Silva, Valle, & Acevedo, 2008). Since it is a sequence of operations, conventional tillage can increase soil compaction (Cotching et al., 2005).

Conservation tillage involves any tillage or sowing system that retains a minimum of 30% of the harvested crop to reduce wind and water erosion of top soil (ASAE, 1993). D'Emden, Llewellyn, and Burton (2006) said that this system is currently popular in Australia, but its use across the regions is affected by economic, management and climatic factors. As a result of residue crop presence, limited runoff, and low evaporation of this system, sufficient water is available within the root growth zone for new crop growth compared with other tillage system (Šarauskis, Romaneckas, & Buragienė, 2009). However, soil under this system for long periods with continual cropping can be vulnerable to compaction (R. Camp & J. Sadler, 2002).

Zero tillage is known as direct drilling or no-till where the seeds grow up in narrow openers in undisturbed soil (ASAE, 1993). It is characterised by limited traffic (typically for fertiliser and/or seed placement) (Botta et al., 2006). Accordingly, it requires lower energy during the growth season and can be economically profitable compared to other systems (Burt, Reeves, & Raper, 1994). Furthermore, Reicosky (2015) mentioned that no tillage can allow sowing without delay, lower fuel cost and soil erosion, improve water quality and infiltration, and increase soil water retention and crop productivity. However, Botta et al. (2008) observed that soil compaction, weed density and root illness are long-term outcomes of this system. The risks of continuous tillage systems can be combated and minimised with deep ripping or occasional tillage operations (Dang et al., 2018; Kirkegaard et al., 2014; Manik et al., 2019).

2.10 Deep ripping

In the late 20th Century, demands for increased daily work productivity and the hours worked per day to achieve food security (due to rising population growth), have led to the use of heavier and more powerful mechanized interventions (McPhee et al., 2015; Odey & Manuwa, 2018). Increased vehicle weight, traffic and frequency of tillage operations with sub-optimal soil moisture contents, have led to increasing soil compaction (McPhee et al., 2015). Generally, deep tillage (Loveday et al., 1970), deep ripping (Ellington, 1987), deep ploughing (Jayawardane & Chan, 1994), subsoiling (Hartmann et al., 1998), deep cultivation (Hamza & Anderson, 2002a) or tilling (Roa-Espinosa (1998) cited in Sidhu and Duiker (2006, p. 1257), is a solution prescribed to ameliorate compacted soils properties (Abu-Hamdeh & Al-Widyan, 2000; Ji et al., 2014; Parker, 2017; Reeves, Rogers, Droppers, Prior, & Powell, 1992) and to preserve the continuity of field productivity (Box Jr & Langdale, 1984; Kuhwald, Blaschek, Brunotte, & Duttmann, 2017; Renton & Flower, 2015; Roper et al., 2015; Scanlan & Davies, 2019). Godwin and Spoor (1977), Godwin, Spoor, and Soomro (1984), Aday (2005), Aday, Ramdhan, and Ali (2016), and Aday and Ramadhan (2019) concluded that deep ripping is quite valuable in clayey soils.

The aim of deep ripping or subsoiling is to loosen the soil profile at a depth below 35 cm for root growth and/or water movement (ASAE, 1993, 2005; Ji et al., 2014). Also, Manik et al. (2019) defined deep ripping or subsoiling as a single or occasional practice to loosen hard and compacted soil layers with sturdy tines to 35-50 cm depth. Whereas Roa-Espinosa (1998) cited in Sidhu and Duiker (2006, p. 1257), stated that subsoiling is a procedure of deep tilling whose working depth ranges from 0.3 m to 0.9 m. However, Reeder et al. (1993) used the subsoiling term in their experiment title, with a depth (28 cm) which does not match the ASAE definition of subsoiling (Standard EP291.2). They justified that, since the tillage tools used were classified as subsoilers, the operation was considered to be on the same terms. However, in this context, from Ellington (1987) viewpoint, the depth of ripping is flexible and related to the restricting soil layer level, so moving underneath by 7 cm -10 cm will guarantee the greatest soil loosening. As the world's arable soils are experiencing low production, it has become imperative to verify deep ripping as one of the compacted soil alleviation solutions for all climatic conditions, soils and farm systems, and its advantages should be presented to farmers to dispel their concerns regarding its adoption (Chen et al., 2005).

When correctly carried out, deep ripping results in greater porosity and free movement of water (infiltration), which in turn increases crop root growth as a result of increasing root penetration/distribution within the loosened subsoil profile. Hence, McKenzie et al. (1985), Jayawardane and Chan (1995), Xu and Mermoud (2001), and Li, Chen, and Chen (2018) have stated that effective deep ripping is likely to benefit yield potential. Similarly, Ji et al. (2014) stated that, as the subsoiling works to increase soil oxygen, it could be an effective way to increase soil enzyme activities, particularly in dense clay soils.

In farms with conventional or conservation systems management, numerous studies have proved that subsoiling is a valuable and effective tillage practice with effects on: 1) soils through increased drainage, loosened compacted layers, aeration and reduced soil strength, waterlogging, runoff, and soil loss and 2) plants through increased roots density and deep penetration and then crop yield and thus, it has become routinely applied in most countries (Raper & Bergtold, 2007).

In compacted clay soils, subsoiling has been recommended to improve drainage through the loosening of layers which, in turn, reduces waterlogging (Gardner et al., 1992; Raper & Bergtold, 2007) and minimises roots dwarfism by reducing soil strength (Busscher & Bauer, 2003; Busscher et al., 1988; Campbell, 1974; Reicosky et al., 1977). In addition, in heavy clay soils which are exploited heavily for cropping and have depleted most of their nutrients, deep ripping modified to place or inject huge N-rich volumes of organic matter into layers during ripping operation, is commonly called sub-soil manuring (Celestina et al., 2018; Gill, Sale, Peries, & Tang, 2009; Peries, 2013). Sub-soil manuring has been also been found to be valuable for other soils. In Canada, the compacted soil of seven research sites with textures ranging from sandy loam to clay loam were subjected to subsoiling with injected pelletised organic matter (Leskiw, Welsh, & Zeleke, 2012). After 150 days, they found out that, the bulk density of sub-soiled fresh organic matter plots was 20% less than either the control (not subsoiled) or subsoiled without pelletised organic matter. Deep ripping was found to be an efficient practice for loosening compacted sodic, acidic or saline soils (Delroy & Bowden, 1986; Hamblin, Tennant, & Cochrane, 1982; Sadras, O’Leary, & Roget, 2005). However, it may also use a gypsum or lime placing technique which also contributes to the improvement of soil structure (Crabtree, 1989; Henry et al., 2018; Matosic et al., 2018; McFarlane & Cox, 1992).

In regions with low rainfall, crop stresses can reduce yields due to limited water for plant growth (Nuttall et al., 2008).Subsoiling helps mitigate plant water stress by loosening soil layers to promote root elongation for water absorption (Busscher, Frederick, & Bauer, 2001). However, agricultural soil may experience a decline in crop yield despite good starting moisture and adequate in-crop rainfall due to the physical, chemical or biological subsoil properties (subsoil constraints) that limit plant growth. Roughly 80% of south-eastern Australia's cropping area has moderate (375-500 mm) and high rainfall (>500 mm) affecting subsoil constraints (Armstrong et al., 2017; Gill, Clark, Sale, Peries, & Tang, 2012) and consequently, slotting or inserting large quantities (>10 t/ha) of organic matter and other amendments during subsoiling operations could improve subsoil structure (Armstrong, Eagle, & Flood, 2015; Celestina et al., 2017), soil properties (Leskiw et al., 2012), crop growth and yield (Gill et al., 2012; Gill et al., 2009).

Despite its advantages, the deep ripping process requires large amounts of tractor power (Blackwell et al., 2016; Isbister, Hagan, & Blackwell, 2016; Pratley & Kirkegaard, 2019) and can become expensive if required annually (Kichler, 2008), making it counterproductive in the short-term impact if not properly applied (Bakker et al., 2007; Perry, 1986; Radford et al., 2000; Soane & Van Ouwerkerk, 1994). Regarding the long life of deep ripping effects, several long-term experiments have been conducted to monitor the alteration in soil properties such as soil strength, bulk density and air porosity, as well as crop production.

In a four-year Georgian (south-eastern United States) study, subsoiling (38 cm) sandy loam soil led to reduced soil strength for the first year only (Threadgill, 1982). Furthermore, at an Alabama Agricultural Experiment Station with pastures of fine sandy loam, cattle were unleashed to graze upon subsoiling with Paraplow down to a depth of 32 cm applied annually in April 1994 and May 1995. The Paraplow effectively loosened the compacted soil and caused an increase in hay dry matter production, however lowered bulk density had returned to the initial values prior to subsoiling due to cattle traffic (Self-Davis, Miller, Raper, & Reeves, 1996). In South

Carolina, subsoiling (60 cm) first year's evidence on a loamy sand soil was found on the second year (Busscher, Sojka, & Doty, 1986). In The Netherlands, the effect of 60 cm deep ripping by blade-type subsoiling on compacted sandy loam soil physical properties was monitored by Kooistra and Boersma (1994). They found that, after three years, the soil re-compacted to the initial physical properties. Likewise, Busscher, Edwards, Vepraskas, and Karlen (1995) stated that over time, the effectiveness of deep tillage will be diminished, and its effects will be completely degraded after three years.

For heavy soils, the results may be different. On a clay soil in Georgia, a Paratill subsoiler with six shanks was pulled close to 30 cm deep, and one year later, soil strength had returned to the initial values, so Clark, Radcliffe, Langdale, and Bruce (1993) concluded that the annual performance of subsoiling in this type of soil may be necessary. After nine months of subsoiling clay loam soil on the semiarid North American Great Plains (Texas, USA) using wheat-sorghum-fallow crop rotation under a no-tillage system, a Paratill subsoiler used to a depth of 30 cm decreased soil penetration resistance and bulk density compared to no-tillage without subsoiling plots. However, applied sweep tillage operations (stubble-mulch tillage system e.g. sweep tillage) had re-compacted the subsurface soil layer and eliminated macropore channels in the subsoiled plots (Baumhardt & Jones, 2002).

Generally, regardless of soil texture, with continued cropping and traffic frequency, soil strength values are very likely to increase and, therefore, yearly deep tillage will be necessary (Busscher et al., 1986; Frederick, Bauer, Busscher, & McCutcheon, 1998; Porter & Khalilian, 1995; Self-Davis et al., 1996; Threadgill, 1982). The need for annual ripping with continuous cropping rotation may be cease when farms are under the control traffic farming system (CTF). CTF is a technique designed to confine compaction to the least possible areas within permanent traffic lanes for machinery (Tullberg, Yule, & McGarry, 2007). Although, slowly adopted because of its conversion and running costs (Audsley, 1981; Gaffney & Wilson, 2003; Galambošová, Rataj, & Vašek, 2010; Kingwell & Fuchsbichler, 2011; Stewart, Copland, Dickson, & Douglas, 1998), the combination of deep ripping with CTF may alter the prevailing perception of being short-lived to one of sustainable impact.

A number of researchers such as Threadgill (1982), Reeder et al. (1993), and Al-Adawi and Reeder (1996) have shown that deep ripping with CTF sustained the positive effects of deep tillage for two years but the combined benefit may actually last for ten seasons (Davies et al., 2012; Raper et al., 1994; Roper et al., 2015). In addition, Raper, Reeves, and Burt (1998) have observed that when traffic is not controlled, subsoiling effects disappeared and subsoiled plots returned to the same compacted (control) physical properties. In a clay soil in Mississippi (south-Eastern United States) using CTF, compared with non-subsoiled treatments, soybean and cotton yields increased by an average 59% and 18% respectively, when the centre (50 cm) of row spacing (1 m) was subsoiled (40 cm) prior to planting (Wesley and Smith (1991) and Smith (1995) experiments respectively). Moreover, in 28 sites in Western Australia, combining deep tillage with CTF resulted in an average wheat yield increase of 550 kg/ha (Roper et al., 2015). As well, to fully realise the benefits of clayey soil cereal production under CTF in south east Queensland, deep ripping was found to be necessary to mitigate soil compaction generated by farming machinery traffic (Hussein, 2018). Furthermore, coupling deep tillage with CTF may reduce the amount of fuel consumption due to a reduction in the amount of power required (Raper & Bergtold, 2007).

Since the main purpose of deep ripping is to loosen the soil compacted layers, the indicators for evaluating the efficiency of this process are largely the same as those used to detect the existence of compaction. Lowery and Schuler (1988) found with compacting soil, the bulk density increased with increasing depth level while hydraulic conductivities of saturated cores decreased with increasing compaction level. The rate change in soil volume calculation or bulk density is one of the simplest and most used evaluation methods. It can be confirmed that there is no research related to compaction or deep tillage without this indicator. Chen et al. (2005) concluded that subsoiling reduced the overall soil bulk density of (0-40 cm) by an average rate of 24% compared with no-tillage and conventional tillage systems. Deep ripping may also have an indirect effect on soil bulk density. Heuperman (2000) and Manik et al. (2019) stated that the deep penetration of dense plant roots due to reduced soil strength after subsoiling may contribute soil bulk density to reduction.

Also, soil strength or cone index is a wide, simple, and in-situ indicator able to assess the efficiency of loosening soil layers via tillage tools (Bédard, Tessier, Laguë, Chen,

& Chi, 1997; Raghavan & McKyes, 1977; Tessier et al., 1997). It has an important presence of most compaction and tillage assessment studies such as Gill and Berg (1967), Soane (1973), Connolly et al. (1997) and Farzaneh et al. (2012). As previously mentioned, the value of soil strength is closely related to soil water content, so it can be said that deep ripping efficiency is affected by moisture availability at the required depth for softening and it also affects soil moisture after it is carried out.

Conducting ripping at the optimum soil moisture could loosen soil with minimum disturbance, facilitate a high percentage of seedling emergence (Hamza & Penny, 2002) and may contribute to a 30% reduction in total operational costs (Araya et al., 1983). Thus, internal soil layers' moisture during tillage determines its efficiency as tillage can result in soil pore blockage by smearing (when soil depth is too wet) (Hodgson & MacLeod, 1989) or dragging large, blocky clods to the surface (when soil depth is too dry) (Lehrsch et al., 1987). It has been found that soil moistures suitable for ripping, in which the soil would not stick to the tines if the soil is wet or produce large clods when the soil is dry, ranged between 6.1% and 6.5 % (gravimetric) of 0-40 cm for sandy soil and approximately 13.3% (gravimetric) of 0-40 cm for clayey soil (Hamza & Penny, 2002; Hamza et al., 2011; Raper & Sharma, 2004).

Regarding to ripping's impact on soil moisture, Chen et al. (2005) observed that subsoiling tillage decreased soil moisture content on the topsoil layer (0-10 cm) by an average of 11%, compared with the conventional tillage. They attributed this to subsoiling promoting deeper water infiltration and less evaporation loss and this agrees with Chamen et al. (2015), Jalota, Khera, and Chahal (2001) and Xu and Mermoud (2001). In addition, Reeder et al. (1993) noticed that the average soil moisture content in the topsoil (10 -20 cm) for subsoiled, subsoiled and trafficked, and control (without subsoil) was 28.4%, 27.7%, and 26.9%, respectively.

Furthermore, rainfall simulation experiments conducted on silt loam soil in Alabama (south-eastern United States) to evaluate the no-till, subsoiled, conventional-till, and rye surface covered systems on runoff (as an indicator of infiltration) and soil loss, showed that subsoiling had an average 22 times less runoff than other tillage systems and more efficacy on runoff and soil loss than surface rye cover (Truman et al., 2003). From their investigation of ripping's effect on the properties of different soil types, Allen and Musick (2001), Said (2003), and Chamen (2011) all observed that subsoiling enhanced vertical water flow in the profile and increased total porosity and macropores.

The appropriate soil moisture seems to produce a non-stirring soft soil, thus it may occupy the same importance as tine design with regards to increasing operational efficiency. In farms with zero or minimum tillage practices, after the crop has been harvested, estimating residue coverage can be used as an indicator of soil disturbance after subsoiling (Reeder et al., 1993). Residue cover retention is an obvious management strategy that could increase soil permeability by decreasing surface sealing (Connolly et al., 1997). Practically, soil disturbance can be relied upon as an indicator of ripping efficiency, or when comparing tillage tools.

Reducing soil disturbance and maximizing residue coverage in conservation systems can be achieved through the correct shank and tillage depth choice, thus the subsoiling operation benefit would be long lasting for both soil and plants (Raper & Bergtold, 2007). Busscher et al. (1988) observed that the disruption zone of subsoiling loamy sand in South Carolina increased with increasing subsoiler shank and point (tip) width. Scanlan and Davies (2019) concluded that in addition to alleviating soil compaction, subsoiling seems to be effective in the long-term when it does not stir soil layers, thus the soil organic component will stay on the top (root zone) instead of being incorporated into deeper layers (Etana et al., 1999). Spoor, Tijink, and Weisskopf (2003) indicated that subsoilers creating fissures are more effectiveness in restoring rooting and drainage than those with massive disruption characteristics. Later, observations by Spoor et al. (2003) were confirmed by Olesen and Munkholm (2007) experiments assessing the subsoiling effect on crop yield on an organic Danish farm which grew a grass-clover mix, wheat, lupin and barley. Dang et al. (2018) mentioned that lowering soil disturbance levels enables microbial communities to recuperate quicker. However, from their review, Chamen et al. (2015) concluded that sometimes, when care is not exercised both during and after ripping, crop yield responses to subsoil loosening can be negative.

In the Reeder et al. (1993) long-term trials, five subsoilers minimized soil stirring (by leaving residue on the surface) by an average 60% compared with a ploughing practice which reduced residue cover to less than 25%. They concluded that the five rippers improved crop growth by minimising soil disturbance, resulting in a uniform, high crop yield for all rippers. Furthermore, Schwab et al. (2002) concluded that subsoiling Alabama's silt loam soil with a Paratill (manufactured by Bigham Brothers Inc., Lubbock, Tex.) and KMC (Kelly Manufacturing Company) subsoiler to depths of 45 cm and 43 cm, respectively, increased the cotton yields by an average 16% than conventional tillage. They attributed yield increase to the findings of Ellington (1987) and Wild et al. (1992): the non-inversion action of subsoiling operations.

Over time, in soils textured with clay >18%, the macroporosity (pores >0.3 mm in diameter) below the first 10 cm will be decreased when they are subjected to intensive and continued traffic and tillage (Connolly et al., 1997; Connolly et al., 2001). Reeder et al. (1993) defined air porosity as a measure of the large pores (cavities) proportion that affects its ability to host air, solution, colloids, and supply them to roots. Accordingly, air porosity value is considered a soil compaction and ripping efficiency indicator (Bruand, Cousin, Nicoullaud, Duval, & Begon, 1996; Lipiec & Hatano, 2003).

Plant root growth is highly likely to be hindered when air porosity measurements are less than 10% at field capacity moisture content (Gupta, 1990). Similarly, to fulfil plant shoot requirements for water and nutrients, soil oxygen concentration should be above 10%, so roots absorb water with enough oxygen for growth (Brady & Weil, 2008; Colmer & Greenway, 2010; da Ponte et al., 2019; Morales-Olmedo, Ortiz, & Sellés, 2015). In Sterling, Ohio (USA), silty clay loam air porosity increased after soil was loosened with each of five subsoilers. However, the benefit of soil aeration ended during the two subsequent trips across the ripped soil. The subsoiled soil without subsequent traffic retained most of its aeration for two seasons (Reeder et al., 1993). From results analysis of various tillage tools' effects on some Egyptian soil properties with different proportions of clay, the subsoiler was superior in increasing total porosity, macroporosity and infiltration (Said, 2003).

In addition to physical soil changes, plant response rate is an indicator that may be reliable when evaluating agricultural operations. Through reduced soil penetration resistance via deep ripping, biomass and grain yield improvement can be achieved (Busscher, Frederick, & Bauer, 2000; Reicosky et al., 1977; Salih, Babikir, & Ali, 1998). Hamza and Anderson (2003) noted that deep tillage alone was responsible for increased crop production in both clay and sand soil. Freeman et al. (2007) also mentioned that biomass measurement during crop growth is a good predictor of crop yield. In one of southern Australia clay soil (55%), for plots with direct sowing (control) and deep ripping (40 cm) before sowing, the dry biomass was measured at the flowering stage of wheat (Anthesis) (growth stage 65 (GS 65), Zadoks, Chang, and Konzak (1974)) while the grain yield was measured at crop maturity (harvest stage) (Gill et al., 2012). They found out that the shoot dry biomass and grain yield of wheat for control plots was 2650 kg/ha, 3600 kg/ha while for ripping treatments was 2760 kg/ha and 4200 kg/ha respectively, and this is consistent with the Freeman et al. (2007) conclusions.

The HI is an evaluation indicator for agricultural operation efficiency through evaluating crop performance. To calculate the HI, the crop dry biomass should be calculated at the end of the season. HI is defined as the ratio of grain yield to the aboveground biomass yield on an oven-dry weight basis (Buah & Mwinkaara, 2009). Moosavi et al. (2013) stated that the purpose of the HI is to show "how assimilates are partitioned among economical sinks and other sinks of the plants". In the Delroy and Bowden (1986) experiment in the Western Australian wheat belt, two weeks before the wheat sowing, Agroplow with 0.33 m shank spacing was used to rip to about 0.3 m in depth. After crop sowing, N applied as Agran 34:0 (NH_4N0_3) at 0, 8.5, 25.5, 50 and 100 kg ha^{-1}, they concluded that both grain yields and total dry matter at season end were significantly increased with ripping high fertiliser doses (Table 2-1). However, they also observed a reduction in the HI for treatments due to decreased availability of water at grain fill which may have fallen at the vegetative growth stage. These results are in line with the results of several studies such as Barley and Naidu (1964), Storrier (1965), Fischer and Kohn (1966) and Fischer (1979). Overall, HI is often non-significant and confusing when compared to the status of crop yield.

In Alabama (south-eastern United States) on a sandy loam soil, a two-year study of subsoiling (30 cm) produced the highest cotton yields for both years of the study (Touchton, Rickerl, Burmester, & Reeves, 1986). Furthermore, the cotton yield of sandy loam soil in central Alabama increased by an average of 22% over the three years of the Mullins, Burmester, and Reeves (1997) study when potassium fertiliser was applied with subsoiling (38 cm) compared with other treatment plots. Also, in Alabama’s silt loam soil, cotton yields of subsoiled plots with a Paratill™ or a KMC subsoiler to a depth of 45 cm and 43 cm respectively, was 16% and 10% greater than conventional tillage and strict no-tillage respectively (Schwab et al., 2002).

Table 2-1 Dry Matter at harvest stage (kg/ha), Grain Yield (kg/ha), and Harvest Index (%) in response to nitrogen application (kg/ha) and ripping (30 cm). This table is derived from the data of Delroy and Bowden (1986)

Nitrogen Applied (kg/ha)	**Dry Matter at Harvest Stage (A) (kg/ha)**		**Grain Yield (B) (kg/ha)**		**Harvest Index ((B/A) ×100) (%)**	
	Not Ripped	**Ripped**	**Not Ripped**	**Ripped**	**Not Ripped**	**Ripped**
0	2400	5900	1200	2960	50	50
8.5	3200	5800	1670	2800	52	48
25.5	3900	7300	2020	3280	52	45
50.0	5200	7500	2510	3320	48	44
100.0	6000	8200	2720	3180	45	39

In Georgia (south-eastern coastal plain, United States), corn grain yields were significantly increased with subsoiling (36 cm) compared with the compacted soil (Box Jr & Langdale, 1984). In Wisconsin (USA), increasing depth of subsoiling implements (a Paraplow and an in-row subsoiler) in compacted silt loam from 30 cm to 46 cm led to an increase in the corn yield, estimated fuel consumption and draught force (Shinners, 1989). In Ohio’s silty clay loam - 40 km southwest of Columbus (United States), after ripping for two seasons, soybean (1991) and corn (1992) yields were 6.1% and 1.8% respectively higher than non-treatment soil yields (control) (Reeder et al., 1993). Similarly, in South Carolina (south-eastern United States), corn grain yields were greater for deep tillage treatments over two years compared with conservation tillage (R. Camp & J. Sadler, 2002). In a field with loamy sand near Florence (South Carolina, USA), treated with a centre-pivot irrigation system, subsoiling applied in 1995 and monitored until 1998 (four years), the result showed that subsoiling increased the corn yield for just two years by an average of 5% (R. Camp & J. Sadler, 2002).

In Denmark, Schjønning and Rasmussen (1994) subsoiled compacted sandy soil was conducted for three consecutive years prior to crop planting. They concluded that during ripping years, the yield had increased and the soil penetration resistance level had deepened from 30 cm to 45 cm deep.

In Nigeria**,** Adeoye and Mohamed-Saleem (1990) found that corn yield in subsoiling clay soil (Alfisols) increased by 1 t/ha (24%) compared to the same soil treated with disc harrowing. They attributed yield increases to the decreased bulk density of 0 cm to 10 cm and 10 cm to 30 cm subsoiling layers by 0.07 g/cm^3 and 0.3 g/cm^3 respectively, which in turn led to improved corn root growth in the subsoiled soil layers.

In The Netherlands, Alblas, Wanink, van den Akker, and van der Werf (1994) found that subsoiling (75 cm) a compacted sandy soil before corn planting increased the yield compared to the control (without subsoiling) during the first year. One year after subsoiling, the corn yield on this loosened soil decreased by 32% as a result of randomly applied loads (10 t/axle). Therefore, they concluded that switching to CTF or lowered applied axle loads was beneficial for sustained subsoiling benefit.

In Canada, on clay soil dedicated to corn cultivation, the compaction was applied yearly from 1982 to 1988 via loads ranging from 10 t/axle to 18 t/axle (compacted plots). Two months after corn planting, subsoiling was performed annually between corn rows from 1986 to 1988 (subsoiling plots). After this research, Gameda et al. (1983) reported that during those three years, the average grain yields of compacted plots was 50% less than the control plots (without compacted and subsoiling) while the average grain yields of subsoiling was 70% more than the control plots. In addition, the bulk density values of subsoiling plots were less than the control plots however, the benefit was temporary due to subsequent annual compaction.

In soil with 60.9 % clay, 36.5 % silt and 2.5% sand in Manitoba-Canada, subsoiling plots had a lower soil moisture content and seeding depth uniformity compared with the no-till and conventional till plots. However, in subsoiling plots crop emergence was much faster, plant populations were higher, and crop yield was higher. These higher values could be attributed to better drainage, aeration, higher temperature, and better water and nutrient adsorption during wet, cold, and dry periods respectively (Chen et al., 2005). They also found that deep root penetration of canola in subsoiled tilled plots (25.4 cm) contributed to a higher yield compared with no-tilled and conventional tilled plots where most roots penetrated to an average 17 cm. A remote analysis was carried out by Schneider et al. (2017) to compare 1530 yield belonging to 65 sites under different tillage systems distributed across Germany, USA, Canada and India. They found that deep ripping increases yield by at least 6% compared to routine tillage.

In conclusion, deep ripping alleviates compacted soils and preserves crop yields. It improves soil aeration and drainage, reduces soil strength and waterlogging, increases soil fertility and improves soil structure when modified with fertiliser, gypsum or lime. It is recommended for wet and dry regions, irrigated and rainfed farms, and for all soil types. However, it consumes more fuel, draft force and money, in the short-term if not managed correctly. By choosing the most suitable design and integrating with CTF, deep ripping could be a global practice overcoming inevitable compaction in farms under continued and intensive cropping and heavy machinery traffic. Despite the number of ripping studies, further investigations of subsoiling clayey soil are necessary to confirm their effects on crop performance and soil properties for prolonged periods (Chen et al., 2005). In Australia, though, it has been a popular practice since the 1980s (McKenzie et al., 1990), with deep ripping going on in different operating conditions, timing, seasons and soils, especially in soils with a high clay content which are characterised by easy compaction (de Lima et al., 2017; Manuwa et al., 2011). Still, it must be studied carefully (Manik et al., 2019).

In addition to subsoil compaction, Australian dryland cropping systems also suffer from subsoil constraints that typically align with soil types, such as water repellence, soil acidity, manganese and aluminium toxicity, and poor fertility which are associated with sandy soils and high alkalinity, sodicity, boron toxicity, chloride, bicarbonate, and salt. These are the common subsoil constraints linked to the finer textured (clayey) soils (Davies et al., 2019). Deep ripping to modify subsoils constraints has been assessed in some Australian Vertosols clayey soils.

2.11 Australian Vertosols subsoil constraints and deep ripping evolution

Australia has the world’s largest area of Vertosols, most of which are found in Queensland and NSW (Dalal, 1990), with high clay content (40-80 g/100 g) (Hulugalle & Scott, 2008; IUSS Working Group, 2014), shrink and swelling features (de Vetten, 2014), unusual and interesting properties (Ahmad & Mermut, 1996), normally ESP (the exchangeable Na percentages) from 2 to 25 near the surface (Dang, Routley, et al., 2006), frequently sodic at depth (Hulugalle & Scott, 2008) and saline (Yule & Coughlan, 1983). Vertosols are mainly devoted to cereal crops, dairying (Hulugalle, McCorkell, Weaver, & Finlay, 2010; Martin & Cox, 1956) and cotton production (Hulme et al., 1996; Hulugalle & Scott, 2008; McKenzie et al., 1990; McKenzie et al., 1983; Wild et al., 1992).

Because of their features, along with an intensive growing history since the 1960s (Chan, 1982), traditional intensive tillage (Greenland & Pereira, 1977), the conventional management (McGarry, 1990), unmanaged soil traffic (Hamza & Anderson, 2005), bulky machinery (Bennett et al., 2019; de Vetten, 2014), subsoil constraints including salinity, sodicity (Dalal, Blasi, & So, 2002; Daniells, Manning, & Pearce, 2002; Irvine & Doughton, 2001), acidity (Ahern, Isbell, & Weinand, 1995), phytotoxic concentrations of chloride (Cl^-), carbonate (CO^{2-}), bicarbonate (HCO^{3-}), and aluminium (Al^{3+}) (Dang, Dalal, et al., 2006; Dang, Routley, et al., 2006; McGarry, 1992; Shaw, Brebber, Ahern, & Weinand, 1994), the Vertosols soils experience poor crop productivity as a result of structural degradation (the compaction) during the middle and late 1970s (Gill et al., 2008; Hulugalle & Scott, 2008; McGarry & Chan, 1984). Pillai-McGarry and Collis-George (1990), Hartmann et al. (1998), McHugh et al. (2009), and Bennett (2016) studies have confirmed that the extent of repair of shrink-swell induced by drying-wetting cycles (Blokhuis et al., 1990; de Vetten, 2014; Hodgson & Chan, 1984) is insufficient for machine induced (traffic) structural degradation rehabilitation.

Deep ripping, deep ploughing or deep subsoil tillage is a relatively common approach in Australian cropping systems since the early 1980s (McKenzie et al., 1990). It has been used for eliminating compaction, destroying hard pans, ameliorating hard setting (Hamza & Anderson, 2002b; McKenzie, Abbott, & Higginson, 1991; McKenzie, Shaw, Rochester, Hulugalle, & Wright, 2003; Schoenfisch, 1999), increasing in total porosity, macroporosity, intrinsic permeability, water availability and soil fertility (Ceja-Navarro et al., 2010; Ellington, 1987; Hulme et al., 1996; Kladivko, 2001), and in this context, has been conventionally practiced at depths of 20 to 40 cm. Despite the importance of ripping on increased yield, it is unlikely to have significant long-term beneficial effects on Vertosols soils (Ellington, 1986; Hamza & Anderson, 2003; Jayawardane, Blackwell, Kirchhof, & Muirhead, 1994; Jayawardane & Chan, 1995) as a result of the continuous decline of organic matter content, biological activity and nutrients (Chan, Bellotti, & Roberts, 1988; Dalal & Mayer, 1986a; Hulugalle et al., 2010; Russell, 1981).

Deep ripping combined with the placement of inorganic (chemical) or organic matter, is one of the current management options addressing Vertosols subsoil constraints and maintaining soil quality (Adcock, McNeill, McDonald, & Armstrong, 2007; Ellington, 1987; Ghosh et al., 2010; Hulugalle et al., 2010). Several studies have been conducted to evaluate the effect of combined deep ripping and deep fertiliser placement on Vertosols subsoil alleviating constraints and improving crop yields.

Nable and Webb (1992) and Holloway (1996) reported substantial increases in wheat yield when zinc was injected with deep ripping. Hamza and Anderson (2002b) and Adcock et al. (2006) observed significant improvements in yield and soil physical properties from deep ripping with different inorganic material. Furthermore, Adcock et al. (2007) mentioned that unpublished studies (R. Graham, J. Ascher and R. Holloway, pers. comm.) carried out in South Australia in the last decade, demonstrated that considerable increases in crop yield (300%) and dry matter (112%) have been achieved when subsoil constraints were ameliorated by the deep placement of fertiliser. Gill et al. (2008) found that deep ripping with organic fertiliser (30-40 cm) doubled biomass production and increased grain yield 1.7 times compared with deep ripping alone.

Clark et al. (2010) observed that subsoil manured at 30 cm - 40 cm leads to increased canola crop production by about 50-80% for three seasons. Similarly, McBeath et al. (2010) found that deep-ripping and deep-placement of fertiliser (35-40 cm) increased wheat harvest weight by 15-128%. Ghosh et al. (2010) concluded that inserting fertiliser with deep ripping improved the Vertosols physical properties by decreasing clay dispersion. Gill et al. (2009) and Gill et al. (2012) reported that subsoil manuring has real potential to increase and enhance wheat and canola productivity. Grain yields of wheat and field peas were increased through the combination of soil ripping to 40 cm with addition chemical fertiliser (Armstrong et al., 2015).

From the above, in can be seen that, as the ripper tine is the first part that penetrates and faces soil resistance forces compared to the injection tube which comes after the shank, the efficiency of deep ripping or deep injection depends mainly on tine design to obtain adequate soil loosening with minimum draft force requirement (Raper & Bergtold, 2007). To improve compacted Australian clayey soils' properties and productivity, there is a need for more investigative trials of existing and new ripper designs, as well as validity checks of draft force prediction models on these soils.

In field investigations that include crop/s, the crop yield component characteristics (e.g. yield of grain and biomass) are precise functions for assessing deep tillage practice, but their results take a long time to appear. In contrast, the cone index (soil strength) is an easy to use, accurate and fast evaluator that gives an instant efficiency reading for ripper and other tillage equipment performance through soil loosening, and is relatively economical (Odey, 2018).

2.12 Cone index (CI)

There is no specific definition for the CI; a number are considered acceptable. Ayers and Perumpral (1982) defined the CI as a measure of soil penetration resistance which, in turn, reflects in-situ soil strength. Bédard et al. (1997) and Tessier et al. (1997) consider that soil penetration resistance, or soil CI, is an in-situ procedure for soil strength which is widely used to assess soil compaction and evaluate the efficiency of agricultural implements in loosening soils. The CI is an expression of the penetration resistance which represents the ratio of force to the cone base area (Upadhyaya, 2005). A penetration test involves driving a steel penetrometer into the soil at a particular speed and recording the soil resistance force against the penetrometer insertion. Thus, CI gives the actual probe specifications and the force required to push it into the soil (Odey, 2018).

The standardized cone penetrometer (EP542 and S313.3 ASABE Standards) is an in-situ simple, familiar device, and quite easy to use. It consists of a polished steel cone of standard shape (an apex angle of 30º and base diameter of 20.27 mm (0.798 in) for light soils and 12.83 mm (0.505 in) for harder soil conditions with a recommended penetration speed of 30 mm/s (ASABE, 1999, 2014). Using hydraulically or electrically operated devices, a standardized penetration speed of 30 mm/s is highly likely to be achieved (Upadhyaya, 2005). Identifying soil strength with a cone penetrometer has been employed for various applications, including determining soil-compaction level (Chesness, Ruiz, & Cobb, 1972; Pagliai et al., 2003; Soane, 1973; Stenitzer & Murer, 2003), tillage implement draft requirements (Gill & Berg, 1967;

Johnson, Jensen, Schafer, & Bailey, 1980), and evaluating earth embankment foundations (Ayers & Perumpral, 1982), resistance to root elongation and seedling emergence (Atwell, 1993; Bowen, 1976; Morton & Buchele, 1960; Taylor & Gardner, 1963), soils abilities to crop growing (Raghavan & McKyes, 1977), and predicting vehicles traction (Freitag & Richardson, 1968; Wismer & Luth, 1973).

Soils with high strength will impede crop development and negatively impact crop yield (Coelho, Mateos, & Villalobos, 2000; Mapfumo, Chanasyk, Naeth, & Baron, 1998; Masle, 1998; Panayiotopoulos, Papadopoulou, & Hatjiioannidou, 1994). High penetrometer readings mean soil strength may hinder root penetration and consequently, high energy will be required by the roots to expand and penetrate the soil pores (Gerard, Sexton, & Shaw, 1982). Various researchers have reported different values of soil penetration resistance at which resistance to root growth is significant: 1800 kPa (Bingham, Bengough, & Rees, 2010; Letey, 1958), 2000 kPa (Blanchar, Edmonds, & Bradford, 1978; Martino & Shaykewich, 1994; Taylor & Gardner, 1963), 2500 kPa (Busscher et al., 1986; Mason, Cullen, & Rijkse, 1988; Taylor, 1971), and 3000 kPa (Atwell, 1993). Soil with a penetration resistance of almost 2000 kPa limits the natural growth of sunflower, whereas root elongation completely stops when penetrometer readings reach approximately 3000 kPa (Sojka, Busscher, Gooden, & Morrison, 1990). The CI value represents the force required by cone to penetrate studied soil. Thus, soil properties have a main effect on cone readings.

CI value depends on soil texture (type), bulk density, moisture content (Chesness et al., 1972; Mulqueen, Stafford, & Tanner, 1977; Smith, 1964; Station, 1948; Wells & Treesuwan, 1978), cohesion, internal friction angle, external friction angle and adhesion (Upadhyaya, 2005). The effects of bulk density and moisture content on CI were investigated by (Ayers & Perumpral, 1982). They concluded that: 1) for soils with a certain percentage of clay, the effect of dry bulk density on CI values increases as soil moisture content decreases, 2) at different soils texture with certain moisture content, the CI increases as the percentage of clay increases and 3) for a specific soil type, the maximum CI occurs with moisture content less than moisture content that yielding the maximum dry bulk density. Many studies have concluded that soil strength is heavily dependent on water content so, its value increases and decrease as the soil dries and is rewet (Busscher, Spivey Jr, & Campbell, 1987; Coelho et al., 2000;

Francis, Cameron, & Swift, 1987; Raper & Bergtold, 2007). Moreover, Voorhees (1983) also noticed that the soil strength value drops after winter. For this, moisten soils with over than field capacity are far more liable to compaction than dried soils (Chamen et al., 2015).

Farzaneh et al. (2012) found that there is a significant correlation of 5% between CI, soil moisture and bulk density qualities in both ploughed and intact soils (without tillage) at different depths. They concluded that: 1) the impact of moisture content on CI results was significant for soils under conventional and nil tillage and 2) soil resistance increases with decreasing soil moisture. They attributed this phenomenon to: 1) reduced pressure of the liquid that fills empty spaces between particles, and in some soils, due to the reduced spacing between particles and then 2) increased soil internal friction angle. Generally, soil resistance increases with an increase in the specific apparent weight and moisture tension of the soil (Gemtos, Goulas, & Lellis, 2000; Mirreh & Ketcheson, 1972).

As mentioned previously, soil susceptibility to compaction increases with an increasing percentage of clay. Therefore, soil resistance to shearing will increase against the ripper tine and tip edges. Increased fuel consumption due to high draft force requirements, lower operation productivity and the increased number of working hours per day due to the low real operation velocity, and the wear and fatigue of machine and engines parts due to heavy duties conditions, all make deep tillage a costly process (Davies et al., 2019).

2.13 Deep ripping cost and benefits

On any farm, higher production costs (e.g. increased fertiliser and fuel requirements) and lower income receipts (e.g. poorer germination rates, crop growth, crop yield and crop quality) are the inevitable result of soil compaction. The level of threat also depends on climate, soil type, depth of compaction and farm typology (Chamen et al., 2015). As it involves high energy inputs, deep ripping is usually an expensive option to mitigate compaction compared with the other tillage systems (Hamza et al., 2011; Kichler, 2008; Kirby & Palmer, 1992; Sabine, 2017) and mitigating strategies (Antille, Bennett, et al., 2016; Chamen et al., 2015). However, from several studies, subsoiling is the most effective technology for compaction avoidance (Chamen et al., 2015; Schneider et al., 2017).

Harrison (1988), Lacey et al. (2001), Manuwa (2009), and Zeng et al. (2017) found that, of the various tillage equipment, ripping compacted soil required high draft force and subsequently more fuel, and consequently deep ripping is an expensive operation. The most obvious incurred cost depends on soil type and operation depth, which both represent a key factor in determining power requirements and fuel consumption (Chamen et al., 2015). With rising global fossil fuel prices since past years (Ndisya, Gitau, Mbuge, & Hiuhu, 2016), fuel costs have become significant component of increasing or decreasing total costs of any agricultural operation, especially deep ripping (Raper & Bergtold, 2007). The cost of deep ripping has been studied several researchers.

Reeder et al. (1993) showed that the costs of deep tillage ranged from USD12/ha to USD44/ha. They stated that these costs were covered through the profits from increased soybean yield in first year, while the second year's profits from increases in corn yield (USD17/ha) represented subsoiling real profit. According to the Mississippi State University Department of Agricultural Economics planning budgets, 2006 which was cited in Raper and Bergtold (2007, p. 464), the total cost of subsoiling compacted soil with a four-tine ripper (1 m spacing) increased from USD26.31/ha to USD27.45/ha to USD33.52/ha for the years 2003, 2004 and 2005, respectively. The planning budgets showed that more than 28.9% was for fuel costs which were USD8.40/ha compared with the other total (fixed and variable) costs of subsoiling in 2005. In United Kingdom farms during the first decade of the 21st Century, the average cost of subsoiling via farmers' facilities was £49 (AUD60.76)/ha and £56.10 (AUD69.56)/ha via contractors' tools according (Nix, 2011). From the derived information of ten farms in southern and eastern England, Chamen et al. (2015) estimated the cost of soil compaction mitigation via subsoiling under different soil types. The typical input levels of conventional farming systems (e.g. tractor power requirement, subsoiler practical productivity, fuel use and price, labour cost, interest, etc.) outlined in Nix (2011) were used in their assumptions. The result of their exercise showed the cost of mitigating compacted clay, silt and sand soil were £56.10 (AUD82.47)/ha, £51.90 (AUD76.29)/ha, and £47.70 (AUD70.12)/ha, respectively. On an Indian sugarcane production farm, subsoiling costs could reach to £45 (AUD55.8)/ha (Kumar, Saini, & Bhatnagar, 2012). Custom rates for deep tillage have been reported in the range of USD32/ha to USD57/ha with USD45/ha given as a typical rate (Ward, 2016).

Improved yield quantity is the positive economic benefit of any farm management option, so profitability would be more satisfactory for the farmer (Chamen et al., 2015; CIMMYT, 1988). The Gross Benefit (GB) or Gross Income (GI) or Yield Gains (YG) per hectare is the product of crop price (per one kg) and the mean yield for each management option. The Total Variable Costs (TVC) is the sum of field operations with seed and fertiliser cost. The Net Benefit (NB) or Gross Margin (GM) per hectare for each management system is the difference between the GB and the TVC. However, from Chamen et al. (2015) estimations of mitigating compaction management strategies' costs and benefits, increasing winter wheat production of subsoiling different compacted soil types has been almost recovered the subsoiling cost without profits compare with other mitigating options such as using low ground pressure tyres, tracked vehicles or CTF system. Consequently, they used the term net cost for the same net benefit or GM equation as profit did not cover cost. However, they indicated that the real profit is likely to come from the higher yields of the next season which is in line with Reeder et al. (1993).

In summary, soil compaction research has been plentiful in the past 25 years but in a very recent review, Chamen et al. (2015) have shown that the cost/benefit data related soil compaction mitigation and avoidance techniques is scarce. Being a costly and difficult process and not particularly palatable to farmers, most deep ripping costs are based on the equation results or yearly report estimation. Thus, compared to the risk of global soil compaction, the number of field experiments studying the costs and benefits of mitigating compacted soils via deep ripping does not match the scale of this problem.

A review of the literature shows that the high costs of deep tillage are mainly due to increased fuel consumption via the tractor engine to overcome the ripper draft force resistance. Various factors related to soil condition, tractor operation condition and ripper design play a fundamental role in increasing draught force, and they should be taken into consideration and managed correctly.

2.14 Energy requirements for soil subsoiling

Tillage systems consume approximately 50% of agriculture’s usable energy (Kushwaha & Zhang, 1998; Namdari, Sh, & Jafari, 2011). Cultivation of clay soils requires high energy and could be greatest when soils are compacted (Botta et al., 2006; Chamen et al., 1990; Jorajuria et al., 1997; Kirchhof, Jayawardane, Blackwell, & Murray, 1995; Pratley & Kirkegaard, 2019). The tractor's total energy output may double in randomly compacted soils (Tullberg, 2010). Thus, reducing energy can be achieved through the proper management of this operation (Ahmadi, 2017; Shmulevich, Asaf, & Rubinstein, 2007). By choosing energy-efficient tillage implements and by properly matching tractor size with tillage implements’ operating parameters, considerable energy can be saved (Ranjbarian, Askari, & Jannatkhah, 2015). The force required to pull a tillage tool through the soil is considered an essential factor in assessing its soil manipulation performance (Mamman & Oni, 2005; Naderloo, Alimadani, Akram, Javadikia, & Khanghah, 2009), determining the correct tractor for the specific implement (Al-Suhaibani & Ghaly, 2010), and choosing tillage implements for a specific farm condition (Al-Suhaibani & Al-Janobi, 1997). Knowledge of tillage equipment energy demands is a pivotal factor for tool design as well as farm management (Novák, Chyba, Kumhála, & Procházka, 2014). Meanwhile, energy demands depend on speed and the draught force (Rodhe, Rydberg, & Gebresenbet, 2004).

Draught force is one of the most important indicators used to evaluate tractor performance efficiency in towing a mounted three-point hitch or pulling a one- or two-point hitch agricultural equipment on or through the soil (Gill & Berg, 1968; Mamman & Oni, 2005; Oni, Clark, & Johnson, 1992; Onwualu & Watts, 1998). Collins and Fowler (1996, p. 203) defined the draft as, “the horizontal component of pull, parallel to the direction of travel, imposed on the tractor by the implement being pulled.” . To study field equipment energy input, connect implement to a tractor and tractor tractive performance, draft force measurements are required (Ademosun, 2014). Measuring the force/s on tillage tools, one of four common instruments could be used: transducer, dynamometer, strain gauge and extended orthogonal ring transducer. Typically, draft force is employed to characterise subsoiler performance and determine subsoiling power requirements (Ahmadi, 2017; Chen, Munkholm, & Nyord, 2013a).

Many of world's researchers have studied the draft requirements of tillage tools and their impact on tractor performance efficiency such as Nichols (1958), Fielke and Riley (1989), Onwualu and Watts (1998), McLaughlin and Campbell (2004), Ademosun (2014), and Lazim, Ashour, and Himoud (2019).

Most researchers agree that the value of the draft force and efficiency of farm-mobile power source vary according to the design of the operating part that penetrates soil, operating conditions and the nature of the soil being disturbed (Araya, 1994a; Bainer, Kepner, & Barger, 1956; Kapuinen, 1997; Warner & Godwin, 1988; Wijesuriya, 1990).

Tine design parameters that affect the draft force include tine arrangement design and tine tip rake angle (Marakoglu & Carman, 2009; Riethmuller, 1989; Slattery, 2003, 2004), tine rake angle (Araya, 1994a; Hann, Warner, & Godwin, 1987b; Kapuinen, 1997; Warner & Godwin, 1988), tine width (Araya, 1994a), tine wing width and angle (Fielke & Riley, 1989; Kapuinen, 1997), wedge tine angle (Wijesuriya, 1990) and tine spacing (Godwin et al., 1984; Godwin, Spoor, Ball, & Munkholm, 2015; Hamza & Anderson, 2008; Hamza et al., 2011; Riethmuller & Jarvis, 1986). In different soils conditions and textures, whether compacted or not, the tine tip configuration is crucial in raising or lowering the draft force value since it is often the first part to touch and penetrate the soil, faces soil resistance to shear, and is the only tine part that works deeply (Hamza et al., 2011; Spoor & Godwin, 1978).

Deep tillage or subsoiling aims to facilitate root growth and water movement by loosening the soil profile to or below 35 cm (ASAE, 2005; Ji et al., 2014). Therefore, deep tillage is the agricultural operation requiring the highest draft force and the most diesel fuel compared to other farm processes (Chamen et al., 2015; Serrano, Peça, & Santos, 2005). It is possible that the amount of fuel and energy could be reduced, or utilised more efficiently, with optimal selection of deep tillage implements and machine operating conditions. Accordingly, subsoiling draft force requirements should be investigated experimentally so growers can choose the appropriate ripper for their tractor’s power with maximum efficiency and determine the costs and benefits of ripping (Chen et al., 2005). Raper and Bergtold (2007) found that the most effective way to reduce the overall costs of ripping is to reduce ripping power requirements.

Ideally, reducing draft force is the first and most important goal when designers draw the initial ripper layout (Xirui, Chao, Zhishui, & Zhiwei, 2016). Design of subsoiler shank plays an active role in draft force requirements. In five different soils, draft requirement increases from 6 kN/shank to 7 kN/shank (by an average of 15%) when the subsoiler shank was changed from curved to straight under the same operating depth (30 cm) (Figure 2-14) (Nichols & Reaves, 1958). Likewise, in Dundee (Scotland) with silty clay loam at 11% soil moisture content, Smith and Williford (1988) observed a similar trend in draft force requirements with parabolic, straight (vertical or conventional), and triplex (conventional with 38 cm wings attached) subsoiler shanks. It was observed that at an engine speed of 2100 r/min and under 54 cm, 52 cm, and 46 cm operating depth for the parabolic, straight, and triplex single tine ripper, the draft force was about 25 N, 29 N, and 32 N, respectively. Raper and Bergtold (2007) indicate that inclined shanks or bentleg shanks that minimize energy requirements while minimally disturbing the soil surface, are equally efficient at various depths of operation. Furthermore, Odey and Manuwa (2018) stated that the force to pull a parabolic tine is, in general, less than the vertical tine. Also, the angled (75˚) subsoiler (S1), having 15˚ chisel rake angle under 37 cm as working depth achieved less draft force (12.4 kN) compared with the vertical (90˚) subsoiler (S2) having the same chisel rake angle and depth (14.2 kN) (Figure 2-15) (Mouazen & Nemenyi, 1999).

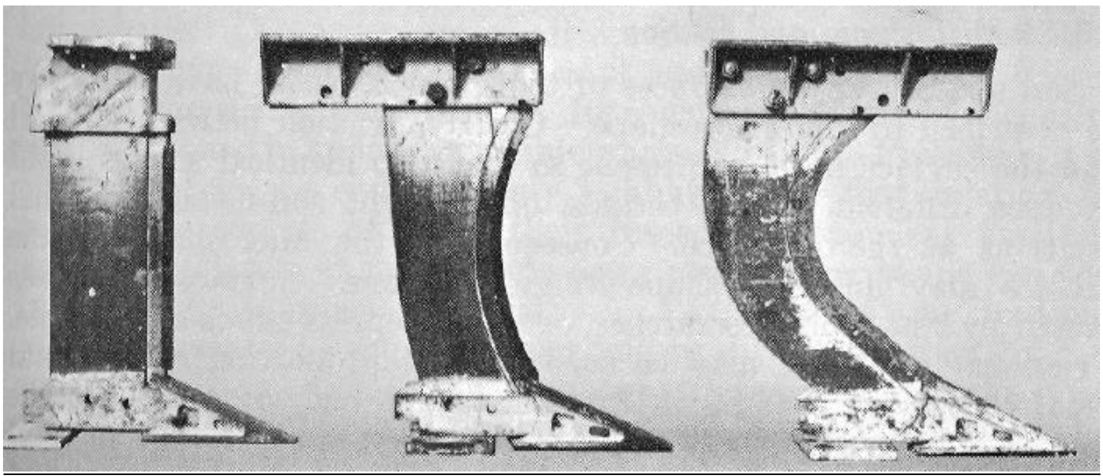

Figure 2-14: Subsoiler shanks used in Nichols and Reaves (1958)

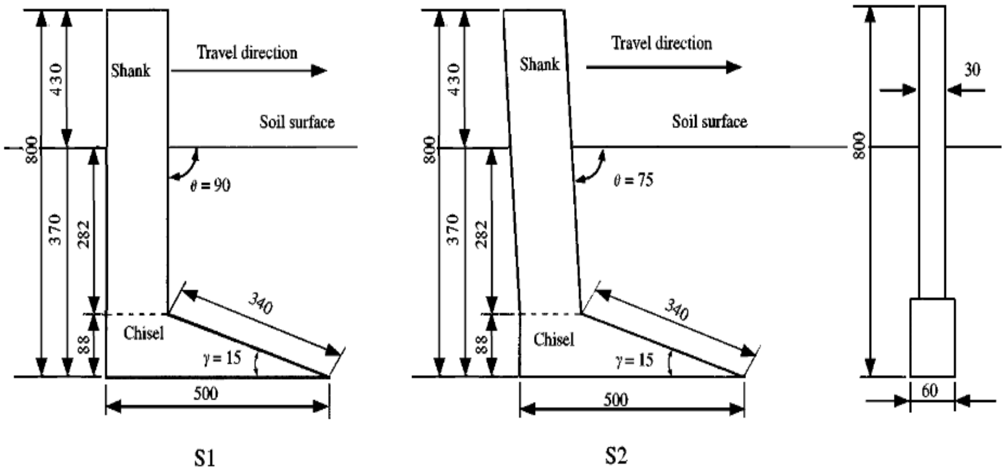

Figure 2-15: : Geometry of straight subsoiler 1 (S1) with 15° chisel rake angle; angled subsoiler 2 (75°) (S2) with 15° chisel rake angle; and the front view of the tine (Mouazen & Nemenyi, 1999)

In contrast, Gill and Berg (1967) found that, for deep tillage, the straight subsoiler is more efficient in terms of reducing the draught force requirements than the curved subsoiler. Moreover, Upadhyaya, Williams, Kemble, and Collins (1984) observed that reduced draft requirements were found for the straight subsoiler shank compared with the curved shank in sandy loam soil.

Similarly, pulling a Kelly Manufacturing Company (KMC) ripper angled shank (45˚) and then Bennettsville curved shank at operating depth of 38 cm in a soil bin with clay loam (sand 27%, silt 43%, clay 30%) increased the draft force from 5.07 kN to 5.671 kN (Raper, 2005). He determined that the angled shank took an average 10.6% less force in the clay loam soil compared to the curved single tine subsoiler. Generally, curved shanks are designed to operate at one depth (Figure 2-16) while inclined shanks can operate at different depths (Gill & Berg, 1966). Finally, to reduce subsoiling energy requirements, minimise disturbance of the soil surface, maximise efficiency under various depths, choosing inclined tines is the perfect solution (Raper & Bergtold, 2007).

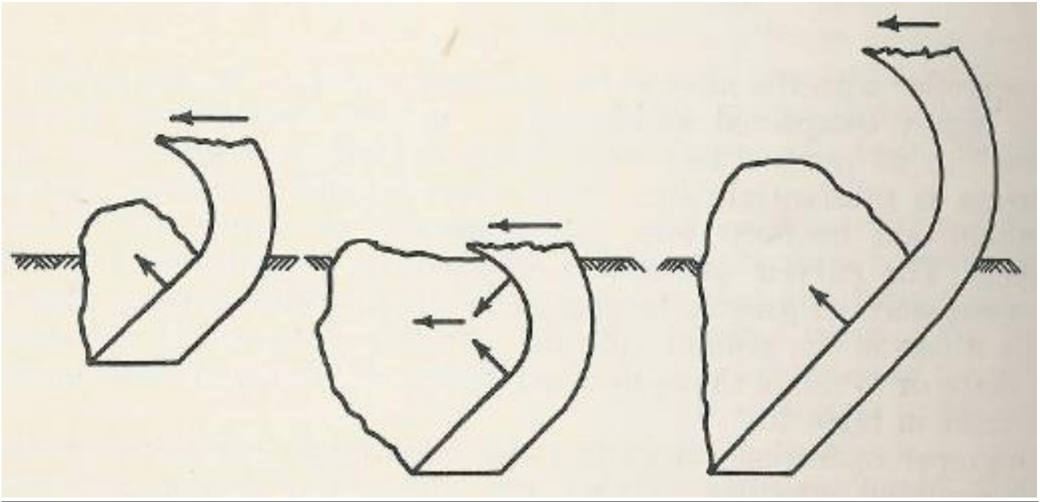

Figure 2-16: Appropriate curvature with shallow depth (left), the inappropriate curvature with deep depth led to increase draft force (centre), and the appropriate curvature with deep depth (right) (Gill & Berg, 1966)

The relative positioning of tines on a tool frame can have a significant effect upon implement performance (Godwin et al., 1984). The findings of Godwin et al. (1984) outlined that minimising soil specific resistance and uniformity of tillage depth can be achieved by spacing tines in the range 1.4 ± 0.25 times the working depth. Hamza and Anderson (2008) concluded that deep ripping to 40 cm with narrower tine spacing than 30 cm was more beneficial in some experiments, but it is unlikely that the advantage was sufficiently consistent to result in increased profit compared to a 30 cm depth by 30 cm spacing combination. Godwin et al. (2015) recommended that for deep tillage implement with narrow points (7.5 cm), the spacing should be arranged as 1.0 - 1.5 times the working depth, while for wide points (with wings 30 cm) the spacing should be arranged to achieve 1.5 - 2.0 times the working depth. Additionally, where using wide tines with wings, with a leading tine, tine spacing of the deep tillage tines should be 2.0 - 2.5 times the working depth.

In heavy clay soils, the draught force of tillage operations can be doubled compared with loose sand soil (Negi, McKyes, Godwin, & Ogilvie, 1978). Similarly, Nichols and Reaves (1958) and Frisby and Summers (1979) showed that the energy required to pull subsoiler in clay soil was 2 - 2.5 times compared to pulling the same subsoiler in sand soil. The ripper draft force in coarse and medium textured soils is estimated to be 45% and 70% respectively, of that for fine-textured soils (Harrigan & Rotz, 1995). Moreover, pulling a KMC angled tine (45º) ripper at first in soil bin with sandy loam (sand 72%, silt 17%, clay 11%) and then in another bin with clay loam soil (sand 27%, silt 43%, clay 30%) at a fixed operating depth (38 cm) increased draft force from 3.68 kN to 5.07 kN (Raper, 2005). Chen et al. (2005) stated that subsoiling clayey soil consumes a lot of tractor power that shackle the implement's working width to increase which considers a significant holdback for subsoiling tillage adaptation by producers. The frequency of deep ripping has also received research attention.

In a field with clayey soil (at the Alabama Agricultural Experiment Station's Tennessee Valley Research and Extension Center in Belle Mina, Alabama, USA) with approximately 33 cm subsoiling depth, three commercial subsoilers including a Kelly Manufacturing Company (KMC), a Bigham Brothers Paratill™ (BBP) and a Bigham Brothers Terratill™ (BBT) (Figure 2-17) and the subsoil frequency application (annual, biennial, and triennial) were investigated from 1999 until 2002. The results showed that the draft force requirements increased significantly from 27.1 kN to 38.3 kN to 45.7 kN when switching from KMC to BBP then to BBT, respectively. Also, the 2002 results showed that the average draft force requirements for the three rippers decreased significantly from 39.0 kN to 38.1 kN to 34.1 kN when switching from triennial to biennial then to annual subsoiling respectively (Raper, Schwab, Balkcom, Burmester, & Reeves, 2005). It can be recognized from Raper et al. (2005) that annual subsoiling

Figure 2-17: Side and front views of KMC subsoiler (left: angled shank (45º) with 2.5 and 4.4 cm of shank and tip width respectively), BBP subsoiler (centre: bentleg shank (45º) with the leading edge rotated forward by 25° with 2.5 and 5.7 cm of shank and tip width respectively and >21.6 cm width contacts with soil as shank travelled forward), and BBT subsoiler (right: bentleg shank (45º) and a slightly narrower version of BBP with 2.5 and 7.5 cm of shank and tip width respectively and >12.7 cm width contacts with soil as shank travelled forward) (Raper et al., 2005)

reduced (improved) draft forces by a 12% compared to biennial subsoiling and 14% for triennial subsoiling which supports what Threadgill (1982) and Busscher et al. (1986) recommended about the need for deep tillage on an annual basis.

The energy required for subsoiling varies considerably with soil strength which, in turn, varies considerably with soil moisture content. Consequently, subsoiling draft force is strongly related to soil moisture content (Mouazen & Ramon, 2006; Mouazen, Ramon, & De Baerdemaeker, 2003; Raper & Bergtold, 2007). Any tine which operates to accelerating and changing the soil particles' locations through movement, must overcome: 1) the internal friction and cohesion of the soil and 2) the friction and adhesion between soil and tine (Kepner, Bainer, & Barger, 1972). According to Nichols (1931), adhesion and cohesion are both lowest at low moisture content (friction phase) and at high moisture content (lubrication phase). Furthermore, ripping compacted soils to the required depth via a conventional single tine ripper moving forward at standard and recommended speed could involve high fuel consumption, draft force and depreciation rate, large clods, and a short time window if the soil moisture content is not suitable (Hamza & Penny, 2002; Hamza et al., 2011; Owsiak, 1999).

In a soil bin at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama, USA, the effect of four gravimetric (dry basis) sandy loam moisture contents (wet: 11.2%, moist: 9.9%, dry: 6.5%, and very dry: 6.1%) on the draft force of two single tines subsoilers (Figure 2-18) included: 1) John Deere 955 row crop ripper straight shank with 3.18 and 12.7 cm for shank and tip (point) respectively, and 2) John Deere 2100 minimum-till ripper shank with 1.9 cm and 17.8 cm for shank and tip (point), respectively. The results from operating the two subsoilers at 0.45 m/s (1.62 km/h) at operation depth 33 cm showed that the lowest average draft force (both shanks) (6.37 kN) occurred in the dry soil condition while the highest average draft force (8.79 kN) occurred in the very dry soil condition. The straight shank consumed an average draft force (5.92 kN) which was lower compared to the minimum-tillage shank (7.87 kN) (Raper & Sharma, 2004).

It is rare to find a field or laboratory experiment evaluating the efficiency of a machinery unit (ripper + tractor) or just ripper tine using a pull meter without employing the speed or depth either as a main or sub factor. Both tractor power requirement and ripper draft force have a positive (upward) linear correlation with operational speed and ripping depth (Mamman & Oni, 2005; Marakoglu & Carman, 2009). However, the researchers' conclusion differed as which one created the main effect when both were tested.

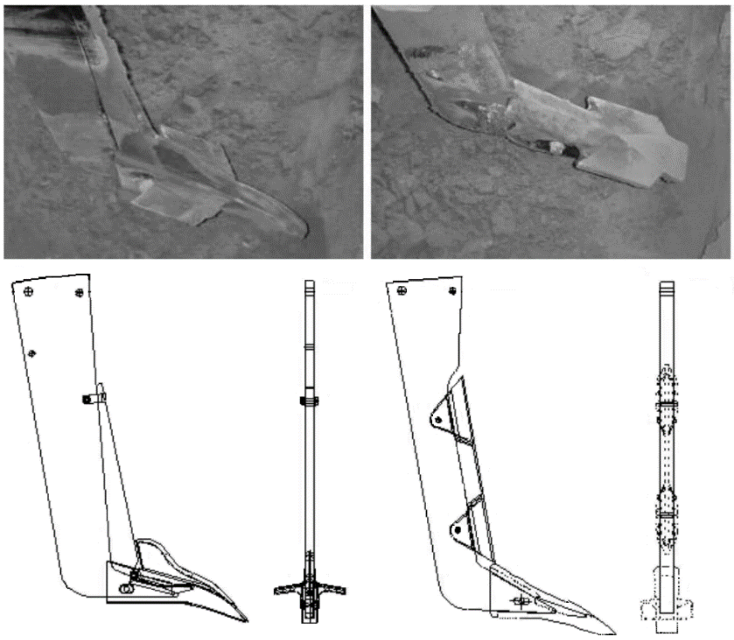

Figure 2-18: Side and front views of John Deere 2100 minimum-till ripper shank with 1.9 and 17.8 cm for shank and tip (point) respectively (left) and John Deere 955 row crop ripper straight shank with 3.18 and 12.7 cm for shank and tip (point) respectively (right) (Raper & Sharma, 2004)

From their closing review's recommendations, Raper and Bergtold (2007) suggested that for a four shank deep tillage implement with 1.0 m tine spacing, coupled to a tractor capable of delivering 133 kW (178.356 hp) drawbar power, the 8.0 km/h (2.22 m/s) forward-speed could reduce the amount of fuel consumption. Also, as the achieved subsoiling disturbance degree tends to increase with increasing forward speed, Weill (2015) has recommended that deep ripping be at a speed of about 5 to 6 km/h to break soil sufficiently. Hamza et al. (2013) ripped Australian compacted loamy sand and clayey Vertosols at a ground speed of 4.3 km/h (1.19 m/s) and 2.9 km/h (0.81 m/s), respectively. According to Bainer et al. (1956) speed is a machinery unit productivity equation input and increasing tiller forward speed leads to increased soil volume and acceleration in front of the plough’s operating part and then increased draught forces. This theory has been confirmed through many field and laboratory studies such (Aday et al., 2016; Kushwaha & Linke, 1996; Owen, 1989; Summers, Khalilian, & Batchelder, 1986; Taniguchi, Makanga, Ohtomo, & Kishimoto, 1999). Smith and Williford (1988) also, concluded that when the ripper velocity increased from 1 m/s (3.6 km/h) to 1.4 m/s (5.04 km/h), the draft force increased from 24 kN to 25.7 kN. Accordingly, tractor power requirement ranged from 24 kW (32.2 hp) to 36 kW (48.3 hp), respectively. Wheeler and Godwin (1996) demonstrated that speed has a negligible effect on implement draught force when it is moving less than the $V_c = \sqrt{5g(w + 0.6d)}$ value (where V_c = critical velocity, g= acceleration due to gravity, $w =$ tine width, and $d =$ tine depth).

Reducing operational speed is one of the strategies adopted by farmers and researchers to maintain the tractor engine power required when increasing ripping depth however, machine productivity will fall (Reeder et al., 1993). Therefore, Shinners (1989) resorted to reducing tractor speed from 3.4 km/h to 3.2 km/h to keep power at about 32 kW (42.9 hp) when the ripping depth increased from 38 cm to 46 cm. As well, Serrano et al. (2005) suggested that power required can be minimised during tillage operations by selecting approximately 70-80% of the nominal engine speed.

However, Grisso, Yasin, and Kocher (1996), Chen (2002), Manuwa (2009), Ademosun, Akande, Manuwa, and Ewetumo (2014), and Ucgul, Fielke, and Saunders (2015) concluded that depth effects on draft force are more pronounced than speed effects. Doubling the tillage operation depth may increase draft force requirements by about 75% (Marakoglu & Carman, 2009). Compared to other tillage equipment, Chen et al. (2005) concluded that the force required to pull a ripper was four times higher than the field cultivator pulling force. They explained that the reason for ripper high draft force in their experiment was related to its operation depth (27 cm), which was three-fold greater than the cultivator (8.8 cm).

Li et al. (2018) confirmed that different operation depths for the evaluated ripper should be studied since it has a considerable effect on ripper performance. Shinners (1989) mentioned that the power required by a tractor to pull the Paraplow ripper travelling 1.1 m/s (4.0 km/h) rose from 28 kW (37.6 hp) to 32 kW (42.9 hp) when the level depth increased from 0.22 m to 0.3 m. For the same purpose, the average draft force for pulling a KMC ripper angled shank (45º) with 3.2 cm thick steel and Bennettsville curved shank with 2.5 cm thick steel (Figure 2-19) in a soil bin with clay loam (sand 27%, silt 43%, clay 30%) under a constant speed of 0.45 m/s (1.62 km/h) at an operating depth ranging from 23 cm to 30.5 cm and then to 38 cm, increased from 0.9095 kN to 2.302 kN and then to 5.369 kN, respectively (Raper, 2005).

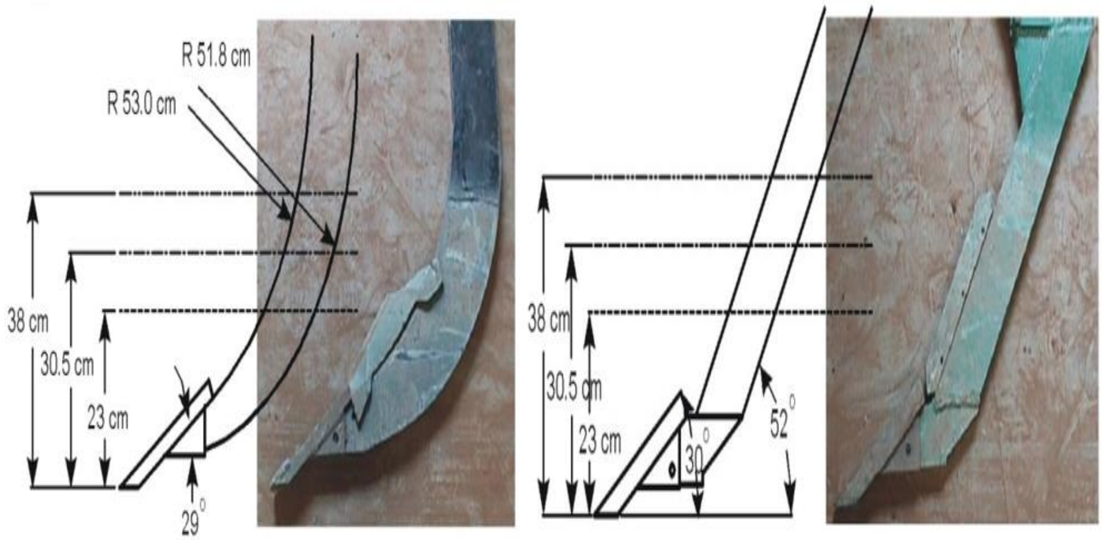

Figure 2-19: Curved (left) and angled (right) single tine ripper in Raper (2005)

In addition to the speed and depth of the soil-penetrated tiller part, the tip cutting edge geometry and its angle (sharpness) affect the draught force value. Fielke (1994) found that increasing the cutting angle increases draught force, while the sharp edge reduces draught force due to minimal soil disturbance action. Increasing the width and rake angle of the soil-penetrated operating tip increases tool draft force (McKyes & Maswaure, 1997; Oni et al., 1992). Three straight single tine subsoilers with different chisel rake angles ranging from 31˚ (subsoiler 1 (S1) to 23˚ for (S2) and 15˚ for (S3)) under constant operational depth and travel speed were evaluated by (Mouazen & Nemenyi, 1999). The subsoilers' geometrical details are shown in Figure 2-20. They concluded that draft force tended to decrease with the decrease in the chisel angle. The small rake angle of 15˚ contributed to a reduction in the draught of the S3 (14.2 kN).

Soil compaction has an effect that is as important as the abovementioned factors and may even surpass them. Generally, tillage equipment working on compacted soil require a draft force ten times greater than draft force when they work in a loose soil (Godwin & Spoor, 1977). In his review on problems associated with Australian compacted clayey soil, Ellington (1987, p. 9) recommended that, "The depth of deep ripping should be related to the depth of the restricting horizon; 7-10 cm below a plough-pan ensures maximum lifting.". However, Zeng et al. (2017) had an opposing point of view when they found that ripping at depths deeper than compaction level

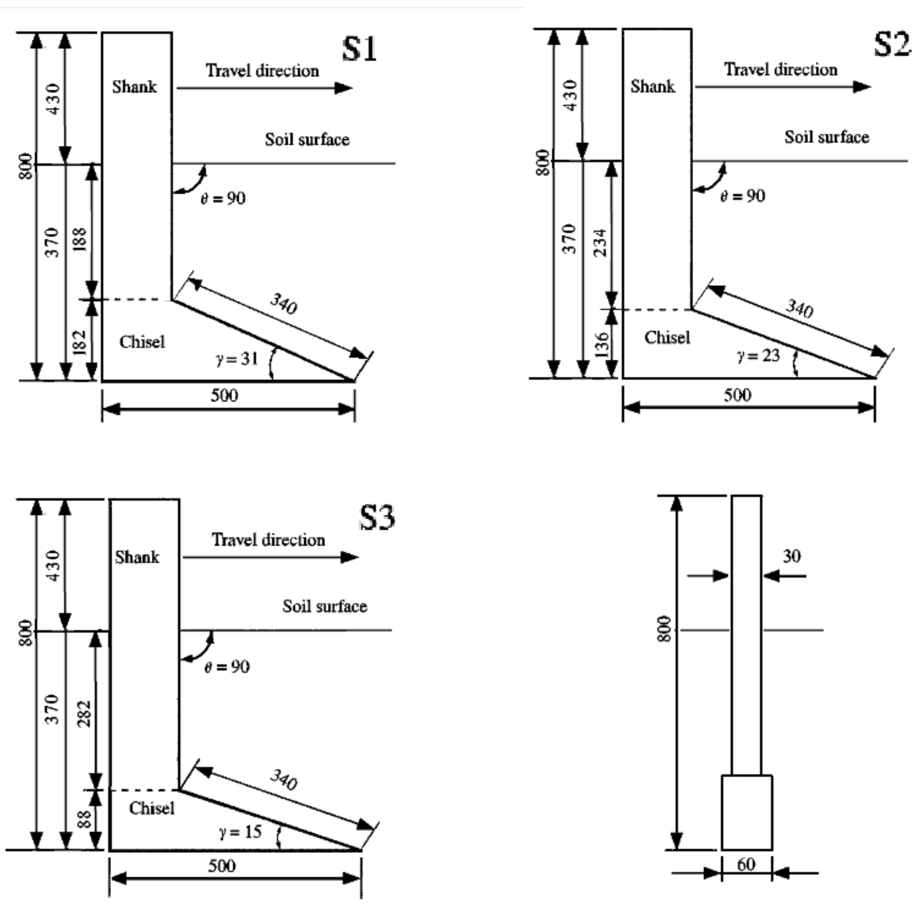

Figure 2-20: Geometry of straight subsoiler 1(S1) with 31° chisel rake angle; straight (S2) with 23° chisel rake angle; straight (S3) with 15° chisel rake angle, and the front view of the straight tine (Mouazen & Nemenyi, 1999)

may lead to wasted tractor energy to loosen uncompacted soil which, in turn, can promote deeper compaction in future years or the disruption of too much crop residue on the soil surface which may reduce crop yields (Raper, Reeves, Burmester, & Schwab, 2000; Raper & Bergtold, 2007). Furthermore, ripping at critical depth "the depth below which soil is not lifted toward the soil surface but rather is compressed to the sides of the tool and moved in a horizontal plane" (McKyes, 1985, p. 75) increases the draft force (Hamza et al., 2011).

With the continued production and employment of heavy and wide equipment and machinery, the risk of soil compaction has become an inevitable reality. In clayey soil that occupies huge areas of arable land, the negative impact of soil compaction on plants may be more severe. No matter how much research has been done in this field, there is still an urgent need to evaluate the new and existing deep tillage tools to overcome this issue under different conditions. Evaluating the compaction and deep tillage impact on clayey soils' properties and its crop productivity is important.

The importance of knowing draft force requirements is considered critical for researchers, designers and farmers. However, regarding tillage equipment, in particular rippers, in-situ procedure is stressful and sometimes dangerous for the executors and may cause deterioration in soil structure, tractor engine, and tiller parts if carried out in wet or dry soil conditions. Accordingly, obtaining approvals to conduct such experiments in commercial fields may somewhat be difficult (as was encountered during this study). Predicting draft force requirements through mathematical models has preoccupied many investigators seeking to overcome the above negatives. The G&O model to predicting the force of pulling a single tine, is a model that has been well received by many researchers, but has not been validated in Australian soils, especially clayey soil (Bennett et al., 2016).

2.15 Godwin and O'Dogherty's single tine force prediction model

Currently, agricultural equipment manufacturers have a clear tendency to increase the size and efficiency of their products to meet continued surges in global food demand as a result of the increasing global population, rising demand for green energies and changes in dietary needs (Bennett et al., 2019; Epule & Bryant, 2015). Increasing farm machinery working width is considered one of the agricultural companies' strategies to increase effective or practical capacity (Antille, Bennett, et al., 2016; Bennett et al., 2019; Bennett, Woodhouse, et al., 2015; Kutzbach, 2000; Mariotti et al., 2020; Poesse, 1992). To increase or maintain the field efficiency of these wider machines within the acceptable range, companies continue to either manufacture large tractors with high-capacity engines to pull or mount or provide powerful motors for self-propelled machines such as pickers. Batey (2009), Bennett, Woodhouse, et al. (2015), Antille, Bennett, et al. (2016), Pulido-Moncada, Munkholm, and Schjønning (2019); and Ashworth, Owens, and Allen (2020) have mentioned that by using heavy machinery, the subsoil compaction risk will rise significantly as a result of the increase in subsoil stresses. Thus, particularly in clay soils, poor physical properties is a result of compaction (Blackwell, Ward, Lefevre, & Cowan, 1985; Kichler, 2008); increasing strength and reducing porosity which causes an increase in bulk density (de Lima et al., 2017; Håkansson & Lipiec, 2000; Horn, Domżżał, Słowińska-Jurkiewicz, & Van Ouwerkerk, 1995; Tullberg, 2000). Soil physical degradation may extend deeper through the soil profile, but the most significant problem will be at a depth of 40 cm especially when soil becomes the target of frequent traffic from powerful and bulky equipment which may exceed 30 Mg (Chamen, 2015). Deep tillage is a remedy for compaction problems (Bennett et al., 2019; Ellington, 1987; Finger, 2019; Jayawardane et al., 1994; Ji et al., 2014).

Despite the importance of ripping for alleviating poor physical properties of compacted soils, farmer acceptance is often impeded by the prospect of excessive tractor power requirements and soil disruption (Ademosun et al., 2014; Manik et al., 2019; Shierlaw & Alston, 1984). Godwin and Spoor (1977) highlighted that, the required power requirements for ripping compacted soil can be 10 times greater than for not compacted soil.

Soil properties are considered a key factor in soil behaviour (Al-Hamed, Wahby, & Aboukarima, 2014). Bainer et al. (1956) and Turpin et al. (2007) confirmed that soil conditions and quality must be considered when designing equipment to reduce draft force and power requirements. However, Upadhyaya et al. (1984) and Ashrafi Zadeh (2006) have shown that working depth, forward speed, working width (operating parameters), tool geometry parameters and soil properties are all the basis of any tillage implement draught requirement. Moreover, according to Aikins and Kilgour (2007, p. 126), “Draught force is a very important variable of interest in tillage implement development and use”. Thus, reducing draft force is one of agricultural machinery designers’ priorities (Jones, Bashford, & Grisso, 1996; Mielke, Grisso, Bashford, & Parkhurst, 1994; Mollazade, Jafari, & Ebrahimi, 2010; Wang et al., 2019).

Traditionally, draught force testing has been employed to evaluate different designs of tillage tools. However, due to the numerous prototypes, testing is time consuming and expensive. Another main obstacle to testing is that the field data is often highly variable due to the non-homogeneous nature of agricultural soils (Li et al., 2018). As a result, it may not be useful in terms of design testing.

By employing computerized predictive programming models, it is very possible to save a lot of effort, time and expense by reducing the quantity of field trials (Catalán, Linares, & Méndez, 2008). In addition, the prediction of draught requirements for tillage operation is very important for researchers and engineers involved in proper design (Ahmadi, 2016; Glancey, Upadhyaya, Chancellor, & Rumsey, 1996) and farmers matching implement size to the prime power resource i.e. tractor (Aikins &

Kilgour, 2007; Rashidi et al., 2013; Shafaei, Loghavi, & Kamgar, 2017). Many researchers have developed mathematical models to predict tillage power requirements by studying soil tillage interaction (Hettiaratchi, Witney, and Reece (1966), Wismer and Luth (1973), Godwin and Spoor (1977), McKyes and Ali (1977), Perumpral, Grisso, and Desai (1983), Godwin et al. (1984), Brown, Gerein, and Kushwaha (1989), Wheeler and Godwin (1996), Godwin and Wheeler (1996), Mouazen and Ramon (2002), and Aluko and Chandler (2004)).

Grisso and Perumpral (1985) reviewed the draft force prediction accuracy of Hettiaratchi et al. (1966), Godwin and Spoor (1977), McKyes and Ali (1977) and Perumpral et al. (1983) models with observation results. The comparison pointed out that the adhesion effect did not exist within the McKyes and Ali (1977) model which considered an important for wet “sticky” soils with high clay content and its value should be measured directly for like these soils (Godwin and O’Dogherty, 2007) guidelines. In addition, both McKyes and Ali (1977) and Perumpral et al. (1983) assumed that the angle of soil-metal friction (δ) is equal to the rake angle to forward horizontal or tine rake angle (α), while Godwin and his colleagues were accustomed to measuring all the relevant soil physical properties whether the soil was pre-prepared or field soil (Godwin & Wheeler, 1996). Also, the final equations of these two models were complicated and included some complex expressions. However, the comparison concluded that two models due to Godwin and Spoor (1977) and Perumpral et al. (1983) were successful in predicting draught and vertical forces and showed good agreement with the experimental results, while Hettiaratchi et al. (1966) and McKyes and Ali (1977) did not succeed in accurately predicting both vertical and horizontal force.

Mouazen et al. (2003) developed a hypothesis that the force required to pull the standard ripper tine could be predicted from the availability of soil bulk density, its moisture and operating depth. However, their model was limited to depths of less than 0.15 m. Further, Mouazen and Ramon (2006) developed their model of draught force giving the following final equation:

$$D = 3.16\, \rho^3 - 21.36\, MC + 73.93\, d^2 \qquad \text{Equation 2-1}$$

Where:

D = draught force (kN),

ρ = soil bulk density (g/cm^3),
MC = moisture content (Kg/Kg), and
d = depth (m).

From their equation, the operation depth and soil bulk density both have a linear effect on draft forces while moisture content has the opposite effect. Although this equation was restricted to shallow depths, too high moisture level may threaten the performance of tillage that aims to achieve deep loosening (Spoor & Godwin, 1978).

According to Manuwa (2009), draught tillage forces are dominated by depth of operation and increase exponentially with increased working depth according to the following equation:

$D = ab^{bd}$ ………………..…………………………..……… Equation 2-2

Where:

D = draught force (kN),
$a\&b$ = exponential function coefficients, and
d = depth (m).

These coefficients then translate to actual numbers. Through a flat plate with 0.05 m in wide and vertical rake angle (90˚) moved in velocity of 9 km/hr (2.5 m/s) under five working depth including 0.035, 0.07, 0.15, 0.2, and 0.25 m on soil bin filled with sandy clay loam soil at moisture content of 11.5%, the exponential equation has becomes:
$D = 82.991e^{0.0091d}$ …………………………………………...… Equation 2-3

The above formula, although mimicking soils with a high rate of sand fraction, does not fit the operating conditions of subsoiling in clay or loam soils.

Recently, Godwin and O'Dogherty (2007) gathered and described most of the model equations that predict the forces affecting tillage equipment (which includes simple tines, interacting tines, cultivating discs, land anchors, and mouldboard ploughs) in relation to their working elements geometry, soil condition and the nature of the soil disturbance in front of the working and penetrating element of the these tools. Godwin and O'Dogherty presented the final equations of these models with a brief description of the development steps, together with their validation against measured forces for a range of tillage tools from their experiments and other researchers trials, e.g. Schuring and Emori (1964), McKyes and Ali (1977), Saunders, Godwin, and O'Dogherty (2000), Saunders (2002) and others.

The quasi-static Mohr-Coulomb failure criterion testing was the basis of the employed models predicting the forces affecting the tillage working parts passing through soil. Tong and Moayad (2006) stated that with the Mohr-Coulomb equation (as follows), the force acting on a failure surface in the soil body can be determined.

$\tau = c + \sigma_n \tan \phi$ .... Equation 2-4

Where:

τ = tangential stress,
c = soil cohesion (kN/m^2),
σ_n = normal stress, and
ϕ = soil internal frictional angle (deg.).

Soil failure occurs when the Mohr's circle reaches the Coulomb envelope as a result of the critical combination between normal and shear stresses (Ahmadi, 2017). Theoretically, the mean value of the predicted force is defined as the maximum force at which the soil failure occurs. According to G&O, the width and depth of the tine is a key factor in determining its behaviour in the soil, soil failure nature, critical depth and the number of acting passive forces. The tine will behave like a blade when its depth/width (*d/w*) ratio is less than 0.5 (Figure 2-21) and soil failure is of a two dimensional nature near the soil surface with soil moving forwards, sideways and upwards and there is no critical depth (Figure 2-22). The tine will behave like a chisel when its *d/w* ratio is >1 and <6, and when the ratio is > 6, the knife will be the tine's behaviour (Figure 2-21). The soil failure with chisel and knife tine's behaviour will be three-dimensional at a critical depth (Figure 2-22).

To determine the tine force components, the critical depth (d_c) determination is required (Godwin & O'Dogherty, 2007). Experimentally, the values of critical depth ranges by which the minimum draft can be achieved force, were found by Godwin and Spoor (1977) and O'Dogherty and Godwin (2003), but they could not specify its location exact. They concluded that, calculated values of the critical depth, became progressively smaller as the friction angle (ϕ) became smaller, while low soil coherence has a smaller effect on critical depth values but was only significantly reduced when cohesion is less than 1. In the same way, the soil inertia effects on tine

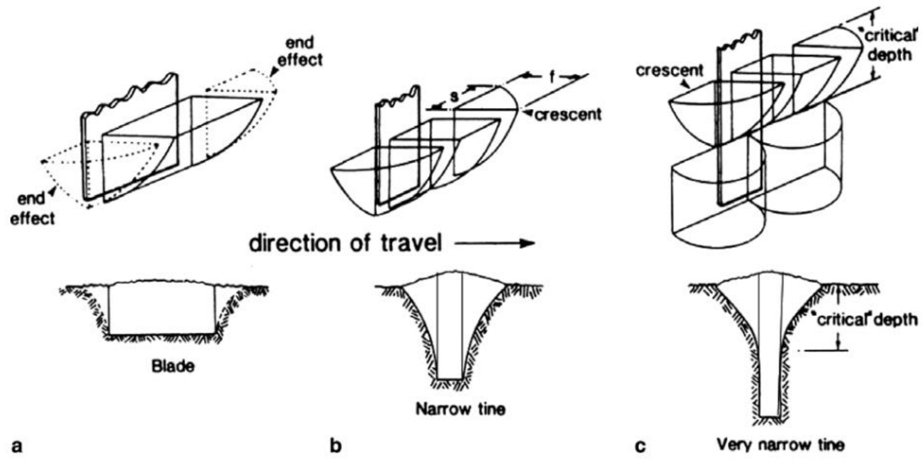

Figure 2-21: The effect of d/w ratio on the tine behave and soil failure dimension (Smith, Godwin, & Spoor, 1989)

forces has been taken into consideration during the model's development. The inertia effects are considered more effective when the tine's speed is critical. Thus, the tine velocity above the $\sqrt{5\text{g}\,(w + 0.6d)}$ (where: w = tine width, g = acceleration due to gravity, and d = depth) must be considered as a critical speed (Wheeler & Godwin, 1996).

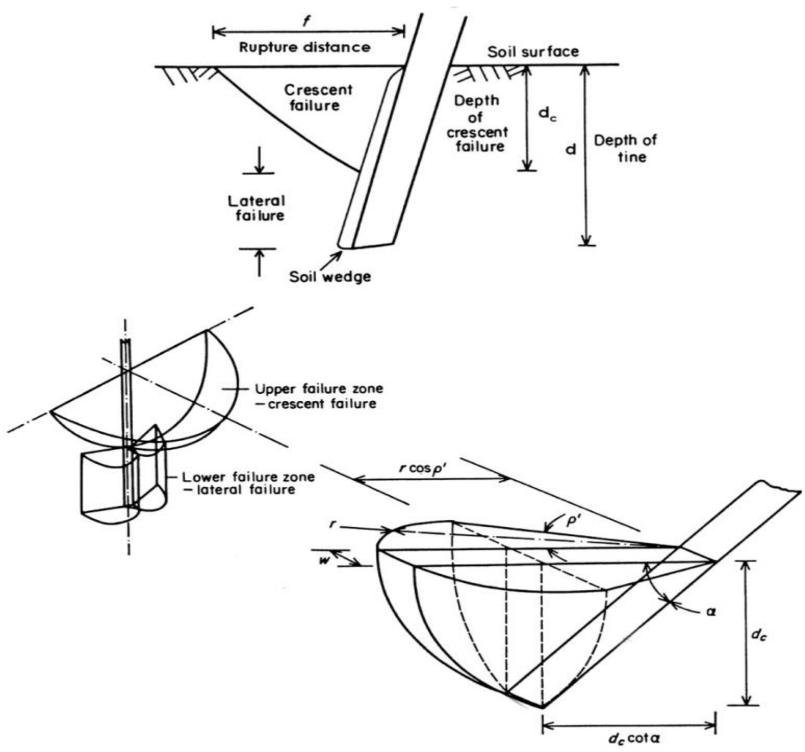

Figure 2-22: The critical depth concept and the soil failure dimensions (Godwin & O'Dogherty, 2007)

Through their many experiments, Godwin and O'Dogherty (2007) have stated that, when verifying the model validity under different depths in a laboratory soil bin, the predicted pull force values were often higher than the measured values with closer agreement between them. In the field soil, the measured pull forces were, in general, greater than the model values with a greater difference, although the variation was within the permissible limits as shown in Figure 2-23. The reason is that, "in the field there was a variation in shear strength with depth which resulted in a greater variation in measured force" while in the soil bin, the predicted pull force was greater than the measured values since the working depth with soil strength were somewhat in equilibrium (Godwin and O'Dogherty (2007, p. 9). Shear strength is defined as "the internal resistance of the soil to external forces that cause two adjacent areas of soil to move relative to each other" (Al-Hamed et al., 2014, p. 85).

Along with increasing tine depth, they pointed out that the width, speed and the rake angle of the tine have the same linear depth effect on the draft force value (Figures 2-24, 2-25, and 2-26). Their study found out that increasing tine speed will lead to increased soil inertia effects, thus increasing the impeding forces on the tine passing through the soil, when the speed is critical. However, the horizontal and vertical forces acting on tine/s could be negligible when the speed is below the critical value which is equal to $\sqrt{5g\ (w + 0.6d)}$ (Wheeler & Godwin, 1996).

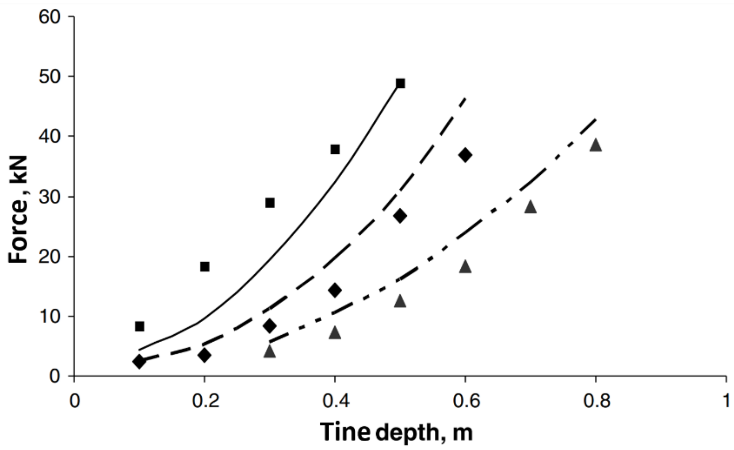

Figure 2-23: Effect of tine depth on the measured (symbol) and predicted (line) for three soil conditions (■ clay (field); ♦ compact sandy loam (laboratory (soil bin); ▲ loose sandy loam (soil bin) (Godwin & Wheeler, 1996)

Increasing the tine width will increase the pull force as a result of the increasing volume of disturbed soil in front of the tine face. As for the tine rake angle, by increasing its value, the tine penetration will increase, and then increase the forward soil rupture distance in front of the tine so the probability of developing the critical depth will be high, thus the final outcome of the draft force will also increase.

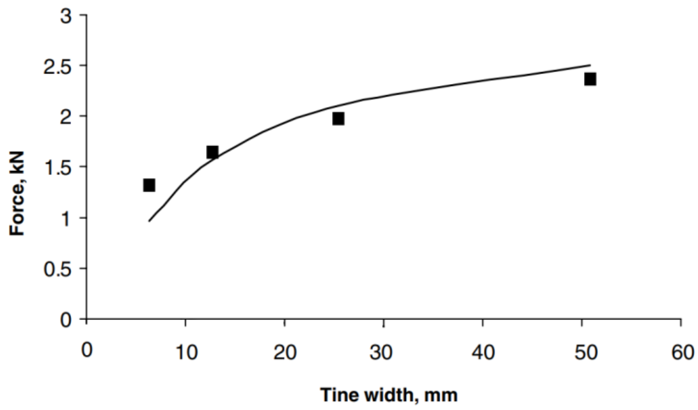

Figure 2-24: Effect of tine width on the measured (■) and predicted (solid line) draft force (Godwin & Spoor, 1977)

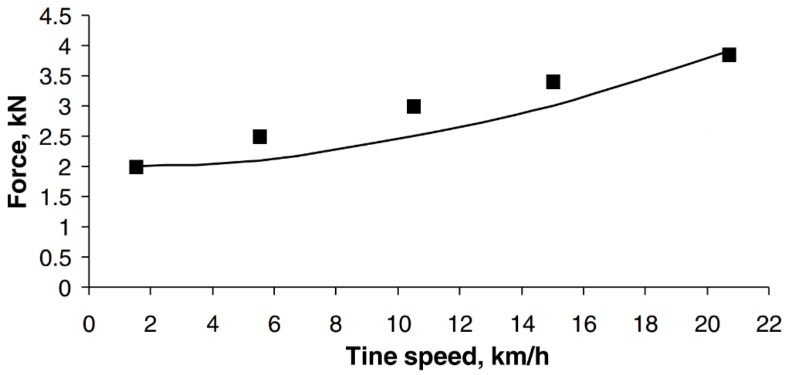

Figure 2-25: Effect of tine speed on the measured (■) and predicted (solid line) draft force (Godwin and Wheeler, 1996)

Even though, implement forces are not difficult to calculate, considerable algorithms and some experience using number of coherent and complicated expressions and derivations, are needed for the final outcomes (Godwin and O'Dogherty, 2007). In order to facilitate the calculations and enable the relevant forces to be easily found, O'Dogherty and Godwin (2003) prepared several spreadsheets which cover simple tines, interacting tines, cultivating discs, land anchors and mouldboard ploughs. According to Godwin and O'Dogherty (2007, p. 12), the advantages of spreadsheets can be captured as follows:

> *Enable both soil properties and implement parameters to be specified by the user. All subsidiary calculations such as the derivation of critical depth and soil N factors are made within the*

spreadsheet structure and entered for the user to view. It is possible to examine the effects of a range of changes in soil and implement parameters on the implement forces and the results can be presented graphically using the spreadsheet facility. The spreadsheets enable comparison of predicted and measured forces. The suite of models provides a means for researchers, designers and development engineers to examine the effects of a wide range of variables for the optimal design of cultivating machinery.

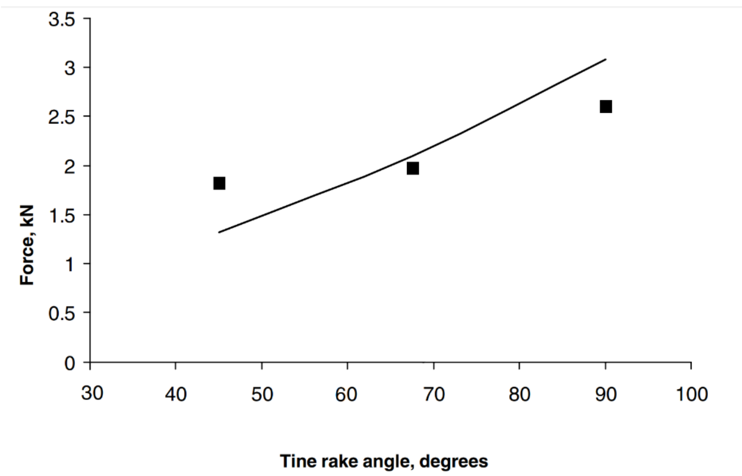

Figure 2-26: Effect of tine rake angle on (■) measured and predicted (solid line) draft force (Godwin & Spoor, 1977)

The measured draught and vertical forces of narrow tines from Godwin and Spoor (1977), interacting tines from Godwin et al. (1984), discs from Godwin et al. (1985); and multiple high-speed tines from Wheeler and Godwin (1996) were compared with the predicted data using O'Dogherty and Godwin's spreadsheets and presented graphically (Figures 2-27 and 2-28). The comparison shows that the models predict the horizontal (or draught) force to within ±20% of the measured forces, with an average error of -3% and the vertical forces to within ±50% of the measured forces, with an average over prediction of 33%. In general, the accuracy of the vertical forces' values are predicting considered more difficult because these forces are:

- Often small in value
- The common tine design is straight (90º), and according to McKyes (2003) cited in Godwin and O'Dogherty (2007, p. 12), the vertical forces for straight tines are difficult to predict due to a mathematical instability in the inertia term, so small differences in this angle during the operation will lead to a significant impact on the direction of vertical force

- The tines may include micro-geometry leading edges and the edge could have a significant effect on the overall force reaction if it is blunt as it is highly likely has a rake angle which differed from the tine rake angle, and the effect will be greatest when the tine design is of straight.

Despite predicted vertical forces eccentricities but for practical applications, the estimated draught force is most needed (Godwin and O’Dogherty, 2007). Nichols (1958) concluded that a main factor in power requirement of any tillage equipment is the horizontal (draft) force which considerably increases with increasing soil resistance to shear compare with vertical force.

Several researchers have dealt with G&O models. For example, Ahmadi (2017), in his study on the subsoiler, mentioned that the G&O model is considered the most widely accepted model that calculates the draft force of tillage implements theoretically. Keppler et al. (2015, p. 309) stated that “Most of the analytical predictions of draught forces acting on wide tines are based on the equation (Godwin and O’Dogherty, 2007) (sometimes referred to as Universal Earthmoving Equation)”. In Denmark, the Universal Earthmoving Equation for the draft force prediction of G&O, was one of the equations used to increase injection tools field efficiency through optimizing its design (Chen et al., 2013b). However, Godwin and O’Dogherty have recommended testing their model's validity in purely cohesive soils or in very loose frictional soils because of the limited availability of data for these soils.

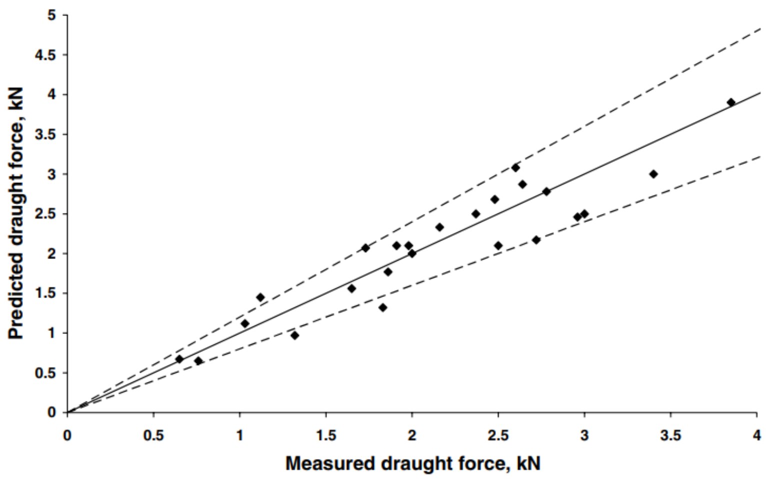

Figure 2-27: Relationship between predicted and the measured draft force (with 20% bounds) for a range of implements and soil conditions (Godwin & O’Dogherty, 2007)

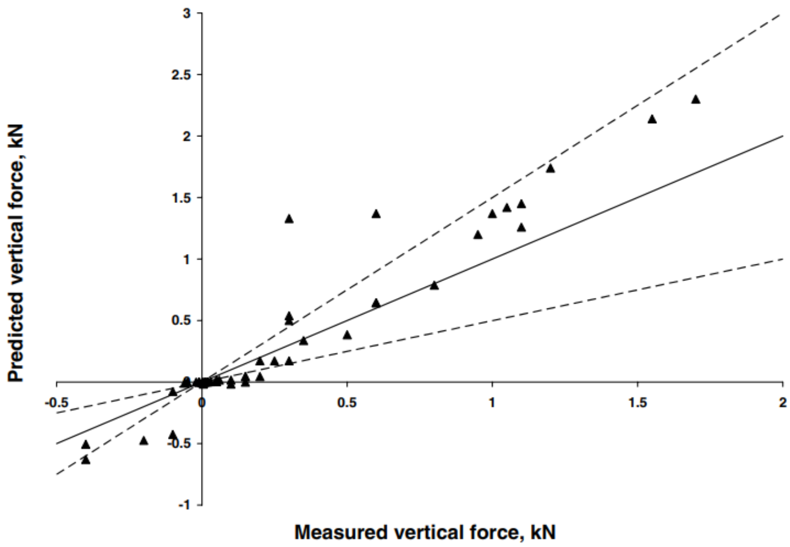

Figure 2-28: Relationship between predicted and the vertical force (with 50% bounds) for a range of implements and soil conditions (Godwin & O'Dogherty, 2007)

In Australia, there is a need to evaluate the soil-tool tillage prediction models with high clay content (Ucgul, Fielke, & Saunders, 2014; Ucgul et al., 2015). Recently, the G&O single tine draft force prediction model validity was investigated by Al-Halfi, Bennet, and Jensen (2017) in Queensland's clayey soil (Ferrosol). However, Bennett et al. (2016), have confirmed that the validity of G&O developed single tine model should be investigated in Vertosols soil to predict draft force and power requirement when removing compaction.

2.15.1 Godwin and O'Dogherty's single tine model description

Godwin and O'Dogherty developed a single tine equation, the draught force (D):

$D = (PW + S\,(w + 0.6\,d_c))\sin(\alpha + \delta) + Q + c_a\,w\,d_c \cos\alpha$ ....…. Equation 2-5

Where:

$P = \gamma\, d_c^2\, N_\gamma + c\, d_c\, N_{ca} + q\, d_c\, N_q$ (d_c = d if $d_c \geq d$);

$W = w + d_c\,(m - (m - 1)/3)$ (d_c = d if $d_c \geq d$);

$S = \gamma\, V^2\, N_a\, d_c / g$ ($d_c = d$ if $d_c \geq d$); and

$Q = w\, c\, N'_c\,(d - d_c) + 0.5\,(1 - \sin\phi)\,\gamma\, w\, N'_q\,(d^2 - d_c^2)$ ($Q = 0$ if $d_c \geq d$)

Where:

D = total horizontal force, (kN),
P = resultant passive force, (kN/m),
W = total integrated tine width (width + sides) affected by forces, (m),
S = lateral force, (kN/m),

Q = lateral failure force, (kN),
w = width of tine, (m),
d = depth of tine, (m),
d_c = critical depth, (m),
α = tine rake angle, (deg.),
δ = angle of soil metal friction, (deg.),
c_a = soil-interface adhesion, (kN/m^2),
c = cohesion, (kN/m^2),
γ = bulk unit weight, (kN/m^3),
q = surcharge pressure, (kN/m^2),
m = rupture distance ratio (where: m = f / d_c, see figure 2-22),
f = forward soil rupture distance, (m),
V = velocity, (m/s),
g = acceleration due to gravity, (9.8 m/s^2),
ϕ = angle of internal shearing resistance, (deg.),
N = dimensionless number (suffixes: γ, gravitational; ca, cohesive/adhesive; q, surcharge),
N' = dimensionless number (suffixes: c, cohesive; q, gravitational), and
N_a = dimensionless number (for inertia).

The G&O developed single tine model parameters are divided into soil and tine parameters (Figure 2-29). Density or bulk unit weight (γ) (kN/m^3), cohesion (c) (kN/m^2), adhesion (ca) (kN/m^2), internal friction angle (ϕ) (deg.), surcharge (q) (kN/m^2), and interface friction angle or angle of soil-metal friction (δ) (deg.) are soil parameters, while depth (*d*) (m), width (*w*) (m), rake angle (α) (deg.) and the velocity (*V*) (m/s) are the tine parameters. Draught and vertical force are the model's outputs.

Typically, bulk unit weight (γ) for many top soils is 15 kN/m^3 but can range between 11 kN/m^3 for a loose dry soil to 18 kN/m^3 for cohesive moist soils. The soil cohesion and adhesion are soil mechanical properties which are major contributors to tillage implement draft force (Plasse, Raghavan, & McKyesn, 1985). Cohesion is defined as soil particles' resistance against displacement due to intermolecular gravitation and the held surface water tension, and it depends on the clay percentage, clayey particle size, clay mineral type, valence bond between particles, and soil moisture content (Jain, Jain, & Bhadauria, 2010). Generally, soil resistance to shear strength is a function of soil particles and intergranular friction cohesion (Graf, Frei, & Böll, 2009). Cohesion (c) is almost zero for dry loose sandy soils and ranges between 5 and 15 kN/m^2 for friable (wet) sandy loam soils. For moist plastic clay soils, the cohesion ranges from 10 to 40 kN/m^2, and may reach to over 100 kN/m^2 for hard dry clay soils.

Adhesion (ca) may be neglected in most of the soils, but it must be taken into account for sticky soils with high clay content and should be measured directly since it has an influential role in the draft force value. For the internal friction angle (ϕ), according to Jain et al. (2010), the value of (ϕ) depends on soil texture, soil dry bulk density, distribution of soil particle size, particle shape and soil moisture content. Theoretically, purely cohesive (clay) soils would have a value of 0°. With increasing bulk density and sand percentage of the soil, the internal friction angle (ϕ) rises to approximately 40° for a compact sandy loam soil, while for friable (loose) sands, ϕ ranges between 25° to 30°. For a clay soil, the typical value of would be in the range 5° to 10° but could reach for 33º (McKyes, 1985). Also, the interface friction angle or angle of soil-metal friction (δ) values are dependent on the soil sand content and linked to the surface finish roughness. Typically, for a sandy loam soil sliding over a steel surface, the δ values range between 20 and 22°, however these values may fall to 15° as the surface finish becomes 'polished'. If δ value not available, it can be extracted from the knowledge of the internal friction angle where δ equals 0.5 to 0.7 of ϕ value according to Godwin spreadsheet guidelines, or it equals 0.66 of ϕ (Mandal & Thakur, 2010). However, finding the value of this angle via laboratory test, gives the precision feature to the model's outputs and reduces expected and legitimate discussions and arguments.

As Section 2.11 concluded, the tine and tip are the physical parts of the ripper that will collide and face soil resistance forces directly, while any part/s tied behind them will be pretty away from the main resistance provided that its thickness is equal to or less than the ripper tine width. This confirms that improving the ripper tine design is not only aimed at reducing the pulling force, but also in improving the performance efficiency of the organic and inorganic fertiliser injection equipment

SINGLE TINE FORCES

This sheet calculates the draught and vertical forces acting on a single tine working in soil.

General Help | Explain Model | Supporting References | Add Calculation Rows

	A	B	C	D	E	F	G	H	I	J	K	L	M
9	NOTES/DESCRIPTION	SOIL PARAMETERS					TINE PARAMETERS					DRAUGHT FORCE	VERTICAL FORCE
11		density	cohesion	internal friction angle	surcharge	interface friction angle	depth	width	rake angle	velocity	rupture distance ratio		
12		γ	c	ϕ	q	δ	d	w	α	v	m	D	V
14		kN/m^3	kN/m^2	deg	kN/m^2	deg	m	m	deg	m/s		kN	kN
15	Notes	Enter values in rows below:									Values rightwards of here are calculated by the		
16	Effect of Depth	15	10	30	0	20	0.1	0.05	30	2	2.36	0.31	-0.26
17	Effect of Depth	15	10	30	0	20	0.2	0.05	30	2	2.36	1.24	-1.03
18	Effect of Depth	15	10	30	0	20	0.3	0.05	30	2	2.36	2.99	-2.48
19	Effect of Depth	15	10	30	0	20	0.4	0.05	30	2	2.36	5.77	-4.77
20	Effect of Depth	15	10	30	0	20	0.5	0.05	30	2	2.36	9.20	-5.19
21	Effect of Depth	15	10	30	0	20	0.6	0.05	30	2	2.36	12.74	-5.17

Figure 2-29: The O'Dogherty and Godwin single tine model spreadsheet input and output parameters

2.16 Optimising tillage tools design, basis for effective injection systems

Strongly moving towards intensive and continuous cropping to face the increasing food demand, requires an equivalent compensation for depleted elements to maintain a positive balance in soil nutrients (Buah & Mwinkaara, 2009; Doran & Smith, 1987; Melaku et al., 2018; Probert, Carberry, et al., 1998). Generally, in the 1970s, injectors started to be developed to apply high fertiliser rates under the soil surface (McKyes, Negi, Godwin, & Ogilvie, 1977; Warner & Godwin, 1988). According to Campbell (1998), the two works of Negi, McKyes, Godwin, and Ogilvie (1976) and Negi et al. (1978) which addressed all aspects of injection mechanization development, have become the basis for the most subsequent studies in this field. Below is a chronological review of some studies which were conducted to optimise and develop injection systems.

In Canada, Feldman and Thuns (1976) designed and built a three-row liquid manure injector unit located in front of a 63 US tons (57 tonne) vacuum tanker capacity. The unit injected about 40 tons (36 tonne) of liquid slurry per hectare via three spring chisel points in 0.86 m spaced corn rows, and not into the tanker wheel tracks. They reported that this system needed an average 87.5 hp (65.25 kW) for pulling and it is suitable for fields 402 m in length. They concluded that a new tine design for the injector system will be included in future work.

In Japan, Nambu, Gemma, and Takekoshi (1979) combined between the injection device and the rotary harrow. All mounted via a 4-wheel driven MB tractor on the rear of a 2.2 m^3 slurry tank (Figure 2-30). The PTO shaft drove an injection pump and the rotary harrow. The rate of slurry depended on travel speed where up to 150 tonnes per hectare inserted to 0.2 m in depth and 1.8 m in width when the speed was less than 0.28 m/s (1 km/h) or up to 50 t/ha, but the speed needs to be ≥ 0.83 m/s (3 km/h) through six vertical pipes connected to main horizontal pipe.

Feldman and Compton (1981) modified their previous injection system to two rows (two tines) adding a cutting coulter and two press wheels to reduce the draft force. In North Carolina (USA), Safley Jr, Barker, and Westerman (1984) provided their research injector with a hydraulic engine, positive displacement pump and a selfweighting system to obtain more accurate data during the experiment. Figure 2-31 shows the modified slurry spreader. The injector unit was three spring loaded chisel points located at the rear of 8517 litres tank which was lifted and lowered hydraulically to inject liquid manure to a maximum depth of 27.9 cm in range at a rate of 177 L/min to 620 L/min through flexible section hoses.

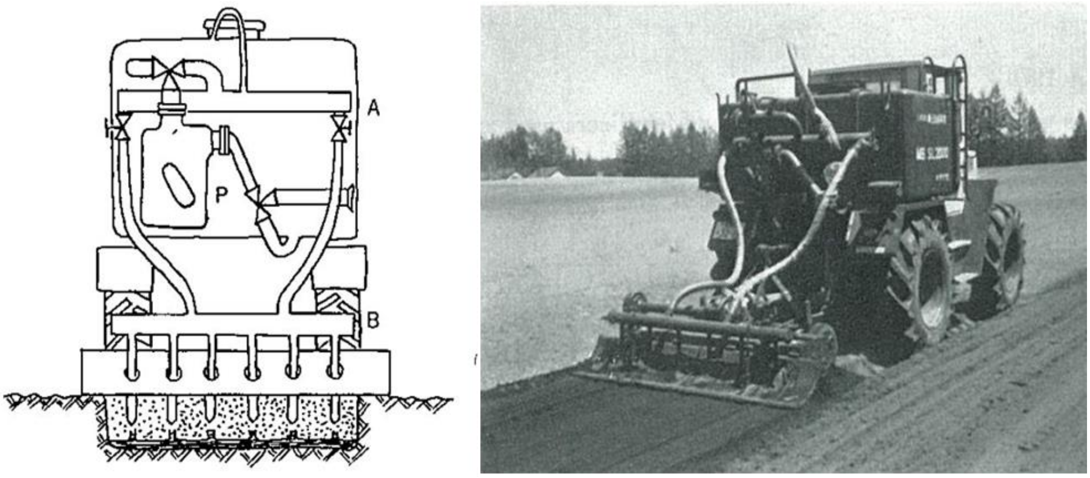

Figure 2-30: Schematic drawing of distributor and injection device (A: horizontal pipe, B: injection device, and P: pump) (left) and the operation of slurry injection via rotary harrow mounted on MB Tractor (right) (Nambu et al., 1979)

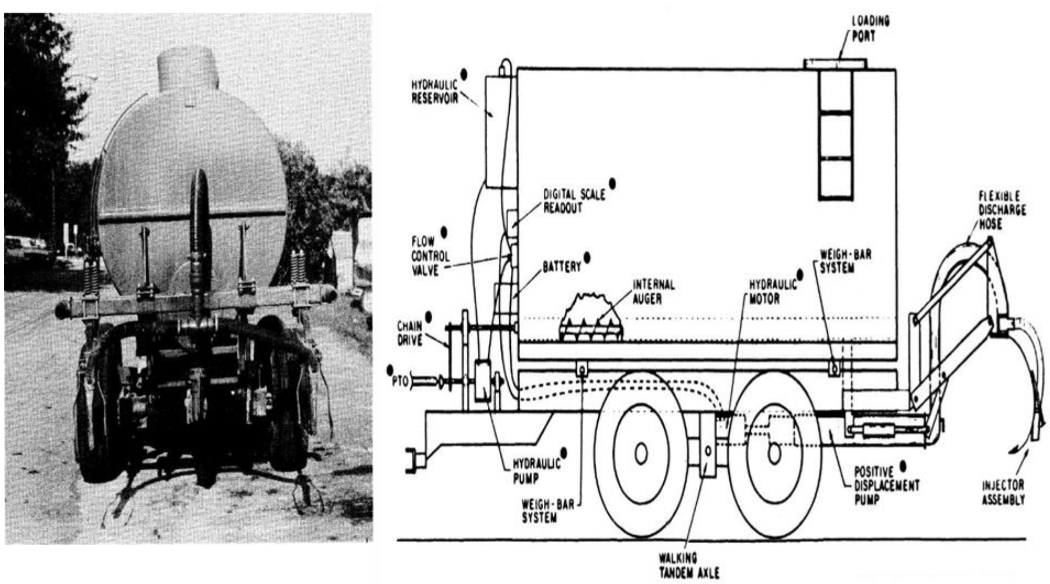

Figure 2-31: The rear of NCSU slurry manure injector (left) and the schematic drawing of the modified NCSU slurry spreader (right) (Safley Jr et al., 1984)

In England, Godwin, Warner, and Hall (1985) used winged tine designs for injection to reduce the draught force while preserving the same amount of fertiliser injected.

They stated that, at a given depth, the amount of injected manure can be doubled using a winged injector compared to a narrow injector. They also stated that by reducing injection depth and increasing soil disturbance width (through wings attached), the considerable force pulling manure injector tines through the soil can be reduced. Therefore, they reported that at a depth of 13 cm, the draught force of winged injector in clay loam soil was 5.4 kN.

In England, Hann, Warner, and Godwin (1987a) indicated that to minimise grass damage, injection tools should create minimum surface disturbance. Soil surface with minimum disturbance through the correct design of an injection tool prevents surface contamination, reduces crop root damage, thus increasing yield. They concluded that the surface disturbance volume reduces with increasing ripper leg rake angle and immediate press wheels behind the injector leg. Through their investigations, they have found that the injector with leg (tine) of 105˚ rake angle, press wheels and an umbilical hose injection system led to an increased grass dry matter yield (t/ha) for clay loam, sandy loam and clay soil by an average of 18%, 40% and 44%, respectively.

New Zealand, which considered a major waste-matter producer (from slaughtered animals and dairy sheds), (Vanderholm, 1984) injected animal blood into the plant root zone as it is a rich N-ready source (13.8% *d.b.*) (Choudhary, Baker, Currie, & Lynch, 1988). They designed a prototype injection machine to inject animal blood into the soil to the root zone (0.075 m - 0.115 m) in 0.3 m-spaced rows at application rates of 25 m^3/ha and 50 m^3/ha using gravity fed system, which was equivalent to 340 kg N/ha and 680 kg N/ha, respectively. To minimize excessive crop root disruption, soil N volatilization, and to promote high retention of vapour-phase moisture, the prototype openers created inverted T-shaped grooves. Seven years later, Abbas and Choudhary (1995) found that 340 kg N/ha × 0.075 m, then 340 kg N/ha × 0.115 m, then 680 kg N/ha × 0.075 m, then 680 kg N/ha × 0.115 m treatments led to 70%, 55%, 62%, and 80% increase in pasture dry matter respectively.

In England, Godwin, Warner, and Hann (1990) compared an umbilical hose system and conventional tanker system. The umbilical system consisted of a pulsating high-pressure pump unit which continuously supplied the injector with slurry through pipes and hoses, allowing the injector to stay in the field all the time (Figure 2-32). They stated that via this system and during wet conditions, compaction occurrence could be reduced since it does not require slurry loaded tankers. Accordingly, the energy demand and required time for subsurface injection of biodegradable fluid waste material will be reduced. They concluded that, the umbilical system cost 20% more than a conventional system but it reduced injection power requirements (25%-50%), fuel consumption (20-30%), odour emissions and ammonia to the atmosphere, manure runoff risks and increased field work rate (10 ha) compared to the conventional system.

Figure 2-32: Umbilical hose system (Pullen, Godwin, Grundon, & Hann, 2004)

In Quebec, Canada, Laguë (1991) mentioned that the existing land application of solid and liquid manure were generally not well adapted for the direct subsurface injection semi-liquid dairy cattle manure (10% solid content). Also, a lower injection rate and excessive tractor power requirements frequently hinder its adoption by farmers. He demonstrated that the high energy and lower rate of injected manure could be avoided with a controlled gravity feed system which created adequate pore space for injecting manure. Prototype systems have been designed, built and tested. The system consisted of a tiltable tank connected to vibrating distribution manifold hoses to direct the manure in four wide sweeps (0.305 m). Injectors spaced 0.76 m apart provided an application rate of over 100 t/ha (37 tons/ac) (Figure 2-33). He reported that, in a firm clay soil at a shallow depth (0.2 m) and a speed of 3.2 km/h (0.89 m/s), the single injector required between 5.03 kN and 6.19 kN of draft force and 4.47 kW to 5.50 kW as power requirements by the tractor.

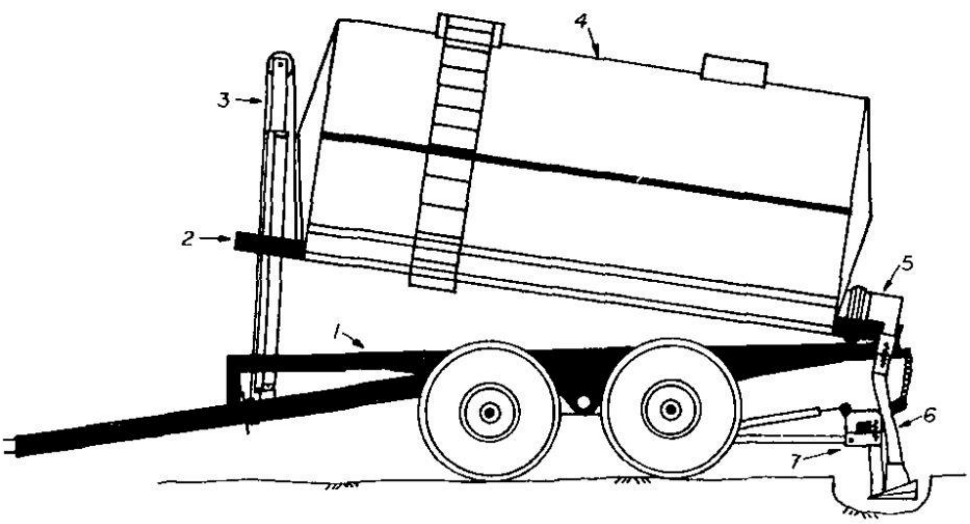

Figure 2-33: Schematic view of the injection machine parts in the operation mode where: 1. Main frame, 2. Tank frame (tiltable), 3. Hydraulic cylinder, 4. Tank, 5. Vibrating distribution manifold (mounted on tank frame), 6. Flexible hose (4), 7. Injector assembly (Laguë, 1991)

In England, livestock manure is a valuable source of fertiliser for crop growth. However, growing concerns about odour, ammonia emissions and the surface runoff of surface applied slurry have led many researchers to either design or modify slurry injection techniques. Warner, Godwin, and Hann (1991) found that manure injection is a liquid manure incorporation technique that can reduce odour and ammonia emission by up to 95% compared to surface application. Nevertheless, under dry grassland conditions, they observed incomplete slot closure and grass death above the loosened zone. They described this die-back due to imperfect injection slot closure and to the extensive root damage due to the excessive surface disturbance. To reduce soil surface disturbance, their design criteria involved: 1) disc coulters placed immediately in front of each injector to cut the sward surface and to prevent residue from collecting on the tine, 2) tines inclined backwards to 105˚, 3) a low-rake angle leading tip, 4) press wheels placed immediately (> 0.88 m) behind tines and 5) a wing with a low-rake attached near the tine bottom. Although their design may also increase draft requirements, it had a positive effect on yield.

In Japan, Araya (1994a) mentioned that in addition to the leg rake angle and tine width, the tine draft force also depends on the soil accelerating force and the soil gravity on the shovel surface. Thus, he introduced a new technology for soil injection of sewage sludge. The theory of his technology is that injecting fluid under high pressure from the nozzle port in front of a tine will led to saturation of the soil zone in front of the subsoiler, lubrication if the tine tip and leg, degradation of the soil structure in front of the injector tine tip, thereby allowing the tine to run in soil with lower shear stress, reducing the draft force and minimizing energy used in the soil disturbance, and may facilitate subsequent tillage operations. Through a chisel injector with a rake angle of 90˚, a shank width of less than 0.015 m, a chisel length of 0.25, a chisel thickness of 0.03×0.03 m, a wheel position at 0.1 m, nozzle pointing of 35° downward, injecting pressurized air (about 1.2 M Pa at the air tank), and tractor speed (less than 0.27 m/s (0.97 km/h), the explosive subsoiler (Figure 2-34) reduced draft force by an average of 30%.

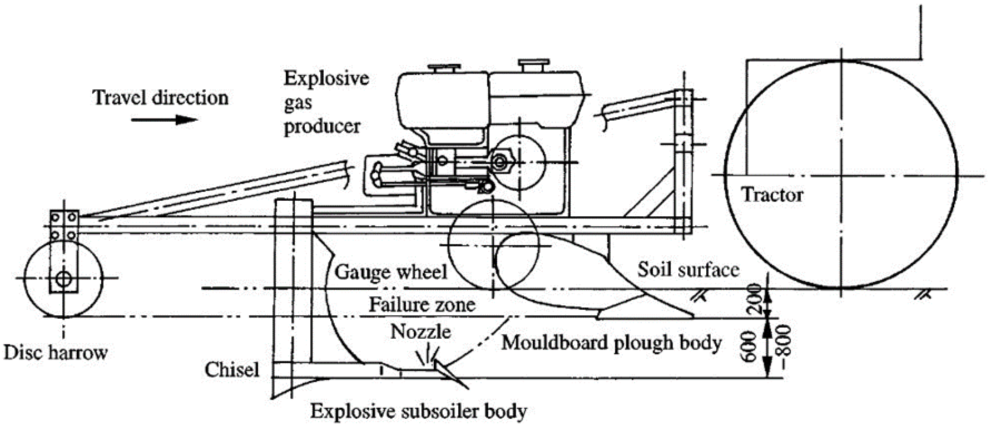

Figure 2-34: The schematic diagram of Araya 1994 explosive subsoiler (Zhang et al., 2000)

In Iraq, locally made tillage (sweep plough) equipment was developed by Al-Halfi and Al-Jasim (2010) to apply liquid fertilisers either on or under the soil surface during tillage, so the equipment had the ability to perform two operations in one pass. The multifunctional fertiliser applicator consisted of a main frame (1.44 m × 0.96 m) mounted on a plastic tank with a capacity of 400 L, and two vertical tines which ended with two wide sweeps (2 × 1 m) with no soil inversion action. Through a powered PTO shaft pump, the liquid fertiliser under pressure of 2 bar (29 psi) could be applied on or below the soil surface with 2 m width via 20 nozzles (Figure 2-35). The developed applicator was evaluated under three travel speeds (3.27 km/h, 5 km/h, and 6.72 km/h), three working depths (0.05 m, 0.1 m, and 0.15 m), with two fertiliser rates (Disper Mg 10% GS) (0.91 L/min and 1.22 L/min) in clay soil (clay 55%, sand 11%, and loam 34%). The overlap between the first speed (3.27 km/h) with first depth (0.05 m) and second flow rate (1.22 L/min) led to lower required draft force (8.62 kN) and highest field efficiency of the injector (69.41%). Higher injector productivity (0.845 ha/h) resulted from the interaction of high speed (6.72 km/h) and discharge (1.22 L/min) with first depth (0.05 m). The interaction between high depth (0.15 m) and fertiliser rate (1.22 L/min) with low speed (3.27 km/h) led to higher soil soluble magnesium (17.40 Milliequivalents Mg per litter (Meq. Mg/L)). Finally, the developed applicator was successful in liquid fertiliser injection under soil surface.

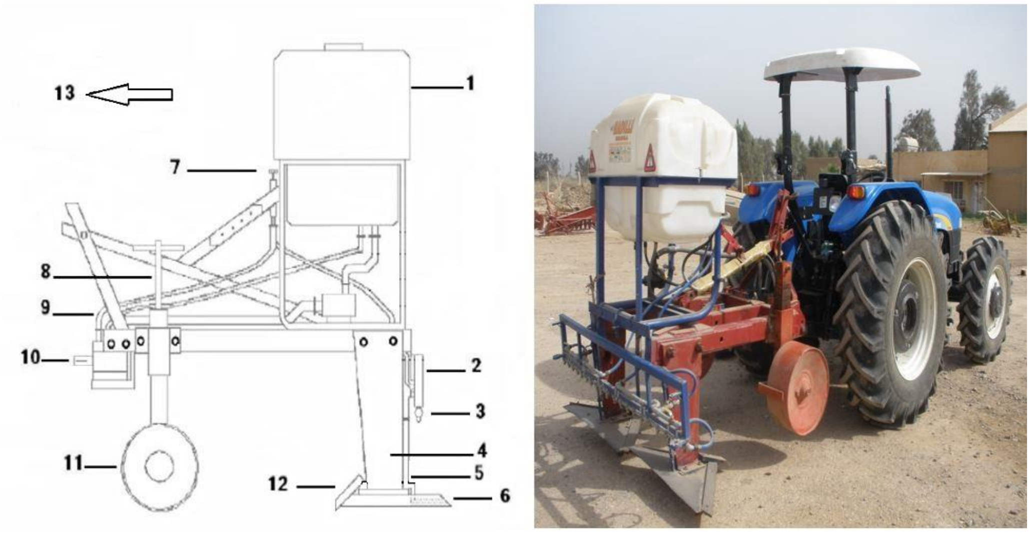

Figure 2-35: Left: the schematic view of the developed injector (left) (1) tank, (2) surface sprayer, (3) sprayer nozzle, (4) straight tine, (5) pipe towards injected nozzles, (6) wing, (7) control valve, (8) depth adjustment lever, (9) delivered hoses, (10) pump, (11) ground wheel (depth adjustable), (12) tine tip, (13) travel direction. Right: the machinery unit (injector + tractor) during the operation (Al-Halfi & Al-Jasim, 2010)

In India, the NPK granules fertiliser is extremely popular and easy to apply. It is commonly applied either by spreading over the whole field and often incorporated into the soil, or in rows. Even so, many authors including Mandal and Thakur (2010) have reported that, in this manner, around 55% of N and 75% of P and K will be lost, either via volatilisation or drifting further into groundwater or combining with soil elements, with the remaining fertiliser effectively used by crops. Also, crop yield profitability will be reduced as a result of reduced crop productivity due to the non-uniform distribution of fertiliser. In contrast, numerous authors such as McEwen and Johnston (1979), Rowse and Stone (1980), Godwin and Spoor (1981), reported that the incorporation of granular fertilisers at different depths ameliorated soil compaction and improved crop yield.

Mandal and Thakur (2010) designed and developed a subsoiler-cum-differential rate fertiliser applicator and tested it in laboratory conditions, and then in a sugarcane field. The equipment consisted of a fertiliser box of 100 kg capacity which delivered dry fertiliser to three winged tines (a main deep and two shallow leading) (Figure 2-36). The design has the ability to place the fertiliser more than 50 cm (main tine) or up to 25 cm (leading tines) to the soil profile in a single pass as well as applying different fertiliser rates of 250 kg/ha, 500 kg/ha, 750 kg/ha and 1000 kg/ha. In the laboratory, he found that the uniformity coefficient of all application rates was more than 90%. He observed that the design increased yield by an average of 22.66% compared to farmer practice (conventional ploughing with in-furrow fertiliser application).

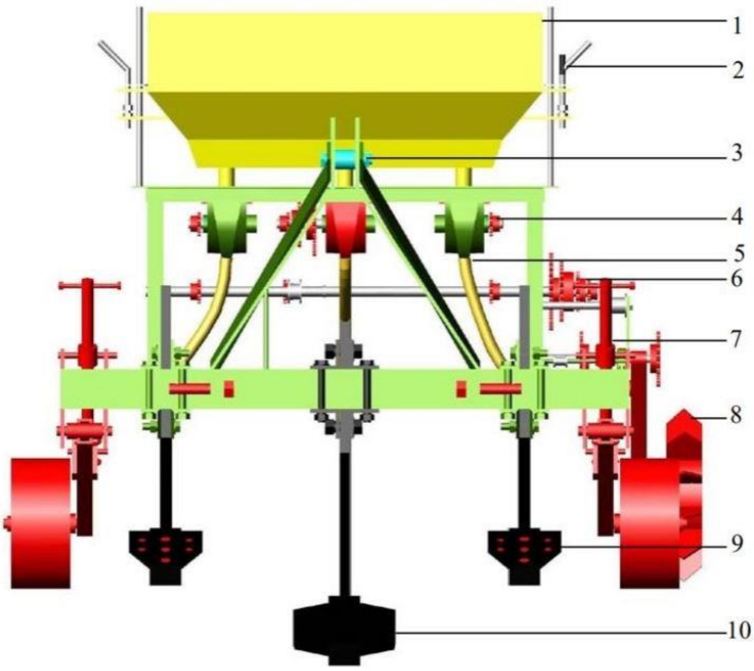

Figure 2-36: The front view of subsoiler-cum-different rate fertiliser applicator with parts number: 1: fertiliser box 2: fertiliser box height adjustment system 3: three point hitch system 4: fertiliser metering assembly 5: fertiliser delivery pipe 6: metering sprockets 7: depth adjustment assembly 8: ground drive wheel 9: shallow winged leading tine 10: main winged tine (Mandal & Thakur, 2010)

In Denmark, the application of animal manure to the soil surface contributes about 25% of the national NH_3 emissions. Earlier, direct soil injection of liquid bio-fertiliser has been shown to considerably reduce ammonia (NH_3) emission and odour. Livestock slurry injection is traditionally done via tankers with a rear attached bar equipped with sturdy spring tines 6 m to 8 m wide and 0.05 m - 0.1 m depth to reduce tractor power needed for tank pulling and pump running. In addition to the limited working width of the tanker with a shallow closed slot injection system, its performance efficiency is reduced in harvested land due to residue accumulation in the front of the tines. Furthermore, using this system during the cereal season could reduce the yield due to crop damage. Thus, this system is limited to the bare ground or pasture. Minimizing injection tools' draft force requirement through optimisation of its design can increase injection working width to ≥ 12 m, operation productivity per hour, widespread adoption, reduced soil compaction and the operational cost. Nyord, Kristensen, Munkholm, and Jørgensen (2010) worked on optimising the injector design to reduce the horizontal and vertical forces, as well as cereal crop damage, in particular, in dry or semi-dry soil conditions with shear strength of 7 kPa or above.

Their new design consisted of two sharpened discs with a diameter of 0.4 m with a tilting angle of 5° with respect to both the horizontal and vertical directions and a rectangular cross-section of 0.1 m × 0.4 m tine with length of 0.6 m and rake angle of 40° and tip rake angle of 45° (Figure 2-37). They suggested that during the operation, the depth should be 0.04 and 0.1 m for disks and tine respectively, with a close distance between them (about 0.25 m) to achieve the goals. Compared with an existing, traditional injector, they found that the new design increased the winter wheat grain yield by 7%, reduced the draft force by 30 - 40%, and reduced damage the during wheat growing period.

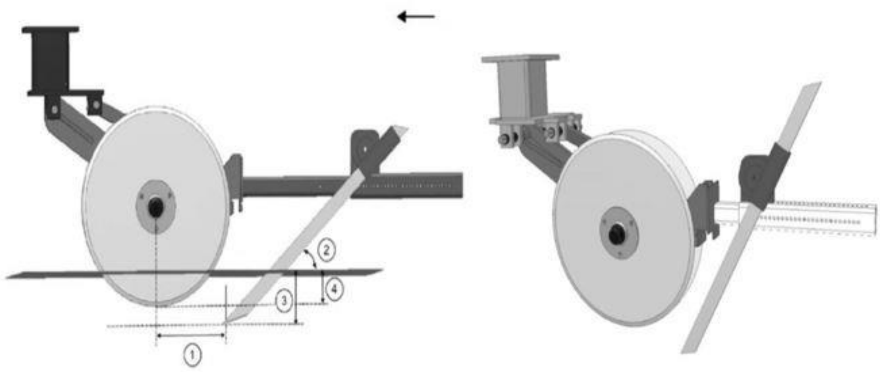

Figure 2-37: The proposed set-up of soil injector during draft force study: (1) distance between discs and tine, (2) 40º - tine rake angle, (3) tine working depth, (4) discs working depth (left) and the discs and tine combination (3D) (Nyord, Hansen, & Birkmose, 2012; Nyord et al., 2010)

In India, Kumar and Thakur (2013) designed and developed a multifunctional fertiliser applicator. The design comprised of three units mounted on a rectangular main frame. The deep soil volume loosening is the first unit positioned exactly behind the tractor rear wheels. It consists two V-shaped tines specially designed to disturb soil without inversion. After the first unit, comes the fertiliser placement unit. It consists of a pair of main fertiliser boxes with 2 × 75 kg capacity and four fertiliser metering housing powered by a floating ground driven wheel at the machine centre. Fertiliser rate of 250 kg/ha - 1000 kg/ha could insert via four inverted -T openers and through rear hoses. To pulverize, consolidate, and level the subsoiled soil, the clod crushing unit was comprised of two floating armed spiked rollers located behind each V-shaped tine. Thus, the design could perform three main tasks in a single pass: 1) loosen the soil profile up to 0.3 m with the first unit, 2) inject the chemical fertilisers to the root zone (0.2 m - 0.25 m) with the second unit, and 3) level the field surface with minimum roughness with the third unit. The design was evaluated in a laboratory and sugarcane field. In the soil bin, it placed the fertiliser uniformly, ≥ 94%. Practically, it managed sugarcane ratoon and other desired operations best with a 55 hp tractor.

In Nigeria, a sweep injector is widely used as it injects liquid fertiliser horizontally in higher rates to a shallow depth after cutting, lifting, and then returning the same soil surface without mixing or breaking (Manuwa, Ademosun, & Adesina, 2012; Moseley, Misselbrook, Pain, Earl, & Godwin, 1998). However, its properties may be affected by a higher draft force requirement, especially in clay soils (Rahman & Chen, 2001). Accordingly, a light and easy installation prototype was designed by Ademosun et al. (2014) to reduce draught force and inject manure into different depths, soils and field conditions. It consisted of two injection tools (convex sweeps (E)) with a spacing of 0.6 m, 30° rake angle, and 45° cutting edge. The injection unit has a flat shaped coulter (D) in its front and curved shank (J) mounted on a 2 m length implement frame for mounting a tank with a capacity of 350 litres (Figure 2-38). The design was: 1) easy to connect, and depth and spacing adjusted and 2) draft force and soil disturbance decreased with shallow injection < 0.1 m. They observed that the design required an average operational draught force of 12.55 kN.

Figure 2-38: Manure injector components (left): (A) fluid-flow regulator arc, (B) depth-adjusting mechanism, (C) coulter bar, (D) coulter, (E) convex sweep, (F) rake-angle regulating arc, (G) furrow covering plate, (H) liquid manure delivery tube, (I) furrow covering plate shaft, and (J) c-shank. (Right): liquid manure injector design during the operation (Ademosun et al., 2014)

Last but not least, in Egypt, to increase tillage and liquid organic distribution efficiency and to reduce operation draft force, modifications were made to the traditional chisel plough by Meselhy (2014). The chisel plough was equipped with a tank of 600 litres capacity and pump powered via a PTO shaft to inject the organic liquid (Root Plus) to about 0.25 m subsurface through hoses located behind each tine. The Root Plus flowed on the blade surface under pressure of 580 psi (~ 3999 kPa) (Figure 2-39). A comparison between spraying and injecting systems simultaneously with chisel till on 0.25 m depth with tractor speed of 5 km/h (1.39 m/s) was done during soil preparation for wheat cropping. The results showed that the new design led to a decrease in bulk density by 3% and soil resistance by 15%, power requirement by 11%, fuel consumption by 11%, and increased soil porosity by 4% and wheat grain yield by 19% compared with the spraying system.

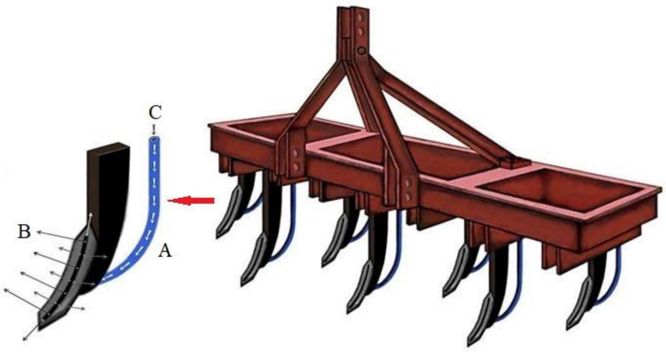

Figure 2-39: Injector tine components (left): (A) manure tube, (B) organic liquid on blade surface, (C) liquid organic material and modified chisel plough (right) (Meselhy, 2014).

It can be seen from the above detailed and simple review, during the last quarter of last century, there was a trend towards reducing required draught force of the primary and secondary tillage equipment. The tine design may be in instrumental in draught force requirement diminution (Huijsmans, Hendriks, & Vermeulen, 1998). Currently, due to intensive farming and heavy machinery use, because of their structural properties, clay soils are the most susceptible to compaction and lack of fertility (Rahman & Chen, 2001). Thus, improved tine design may be the most effective solution by: 1) reducing the tractor power required to alleviate compacted soils and 2) simultaneously improving soil fertility through shallow or deep injection of organic or inorganic fertilisers.

From the above review, it can be concluded that the aim of the tine design is to reduce draught force, fuel consumption and costs, and increase the efficiency and productivity of operation. Another goal of tine design is to develop crop and forage production. With the correct design, the availability of soil water for plant growth will be greatly increased by improving soil physical properties.

Many studies have confirmed that the Australian agricultural sector is being affected significantly by climate changes (Field et al., 2014; Garnaut, 2008, 2011; Williams et al., 2015) and soil structure degradation (Cook et al., 1992; Dalal & Mayer, 1986a; Dang et al., 2018; Gill et al., 2009; Hulugalle & Scott, 2008). Thus, in the future, Australian cropping regions may experience significant changes in agricultural production rates due to the decline in available surface or ground water resulting from reduced falling amounts of rainfall (Authority, 2010; Brennan et al., 2003; Williams et al., 2015) and soil compaction (Antille, Bennett, et al., 2016; Bennett, Woodhouse, et al., 2015). Under these circumstances, the biophysical simulation model, APSIM, will enhance decision-making regarding the reduction of future risks' impacts on the economics of crop and grazing industries (Williams et al., 2015).

2.17 Crop performance modelling

Generally, to attenuate of Australian's environment impact (especially the runoff and erosion) on cropping production, the conservation tillage systems (stubble mulching and minimum or zero tillage) have been widely adopted since 1989 to replace the conventional or frequent tillage practices that was adopted since 1960 (Tullberg et al., 2001). The use of these systems in Australia's rainfed agricultural zones is characterised by a variation in crop yields due to: 1) subsurface structural degradation through soil compaction which is a largely product of normal machinery traffic during season crop production, 2) high temperatures (Pierrehumbert, 1977) and 3) severe water shortages (Brennan et al., 2003). In these zones, the percentage of rainfall infiltration and runoff is essential for water availability; the key constraint on crop yield (McHugh et al., 2009; Nuttall et al., 2008; Tullberg et al., 2001). Deep tillage practice within conservation cropping systems has been approved as a soil compaction alleviation solutions (Lindstrom & Voorhees, 1994) through improved the infiltration rates (Raper & Bergtold, 2007) and reduced evaporation loss (Jalota et al., 2001; Xu & Mermoud, 2001). Both climate and farm management factors have a significant impact on soils structure, water and crop growth (Tullberg et al., 2001). Given the impossibility of isolating these factors under field conditions (open system), the most complex issues facing the interpretation of crop productivity experimental results is the inability to determine which factor has the actual effect on crop yield and performance. Currently, the complex issues have become no longer impossible. With the use of simulation models, it is now possible to check the effect of the intended factor while keeping the other factors constant (not activated).

According to Probert et al. (1995), a model is a regression equation that fits experimental data. Also, Carberry and Bange (1998, p. 154) defined the simulation model as "a mathematical representation of an aspect of the real world.". Most agricultural experiments face many constraints such as prevailing climatic conditions, distribution of random factors, breadth in experiment period and size. Consequently, models complement experiments, dealing credibly with crop conditions such as climate, soil, water and farm management practices (Probert, Dimes, et al., 1998). Therefore, simulation models are powerful tools when formulating farm management policy that prepares for future local and global environmental risks and assesses crop productivity under related long-term impacts (Challinor et al., 2014).

The simulation models are tools to support and improve farm decision-makers' abilities to: 1) study and analyse available alternative strategies that increase farm productivity and profitability (Ventrella, Charfeddine, Giglio, & Castellini, 2012) and 2) address climate variability risk and natural resource consequences such as rainfall and soil nutrient depletion (Palosuo et al., 2011; Probert et al., 1995). Models can be used to evaluate the impacts of uncontrolled pressures on farm productivity (such as climate variability) (Asseng et al., 2013; Van Ittersum et al., 2013) selecting the appropriate, alternative farm management strategies to deal with these conditions and assessing their long-term efficiency (Probert, Dimes, et al., 1998).

Generally, models simulating crop growth aim to clarify the mechanism/s between simulated variables and parameters as well as among the dependent variables, so they generally are mechanistic models (Porter & Semenov, 2005; Rauff & Bello, 2015). According to Pittock and Nix (1986) and Challinor, Ewert, Arnold, Simelton, and Fraser (2009), crop growth simulation models contain central engines that create a required combination of variables to produce predictive values for the intended parameters, so they are mechanistic models.

The Agricultural Production Systems sIMulator (APSIM) (Holzworth et al., 2014; Keating et al., 2003; McCown et al., 1996) is one such adopted model

2.18 The Agricultural Production Systems sIMulator (APSIM)

In the early 1990s, work began to design and build the framework of a simulator with the ability to represent farm management guidelines (Holzworth et al., 2014). Several external models (ancestral) were married (incorporated) and gave birth to AUSIM (McCown & Williams, 1989) and PERFECT (Littleboy et al., 1992) (parents). AUSIM and PERFECT were married and gave birth to APSIM (grandson) (Figure 2-40). To fulfil the basic purpose of a simulator, the crop seasons, soil and system management dynamics became the centre of the simulator's design. APSIM can simulate different production systems (McCown et al., 1996), above and below ground crop growth, and soil water and N uptake (Asseng, Anderson, et al., 1998).

APSIM consists of a series of plug-in/pull-out modules connected to a central interface engine which enables the simulation of climate and soil condition effects on the performance of a single crop or a cropping system, evaluate farm management (e.g. tillage, irrigation, fertilisation etc.) and its interactions, and crop type, timing and sequence within flexible or fixed agricultural rotations (Wang et al., 2002). Simply put, APSIM as computation unit represents a collection of modules (e.g., crop or water balance) that simulate processes (e.g., photosynthesis or runoff) which, in turn, interact with each other on a daily timestep (Holzworth et al., 2014). For example, the module

SOILN simulates the process of N mineralisation and N availability to a current crop from the soil, residue roots and previous crops (Keating et al., 2003).

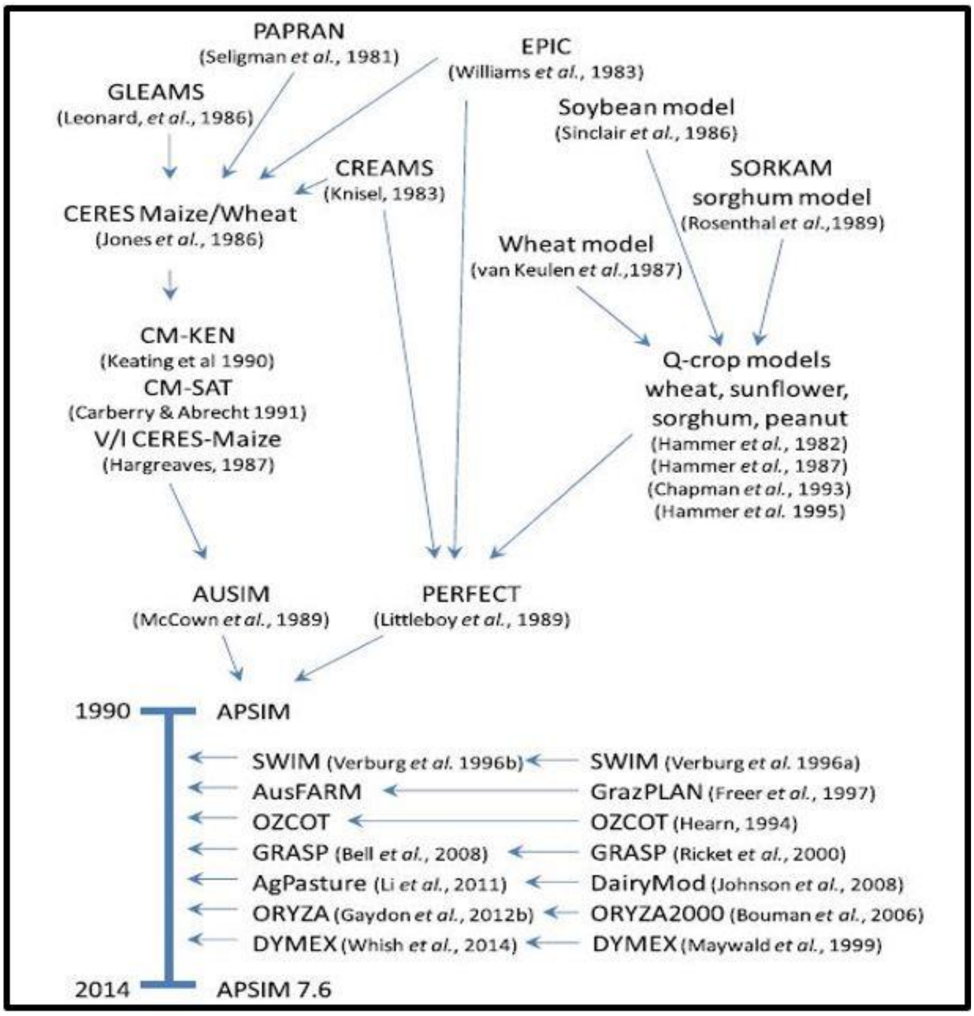

Figure 2-40: The model pedigree of APSIM (Holzworth et al., 2014)

The initial software was developed by the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003). Through nearly 25 years of continuous research and development and integration of other models and related scientific groups (Figure 2-40 and Table 2-2), the version APSIM 7.6 was released in 2014. Plant, soil, animal and climate are the biophysical models are offered by APSIM. According to Holzworth et al. (2014), the growth of plant organs (e.g. leaf, stem, root, and grain), distribution of biomass and N between organs, absorption of water, nutrient, and carbon, and responses to abiotic stresses are the key physiological processes simulated by the plant models. Water leakage and movement, evaporation, runoff, degradation, temperature difference and nitrate cycling are the soil surface and subsurface processes simulated by the soil models.

Table 2-2: The plant, soil, animal and climate models built in the initial version of APSIM 7.6 (Holzworth et al., 2014)

APSIM model	Origin/references	APSIM model	Origin/references
Plants		Sorghum	(Hammer et al., 2010)
AgPasture	(Li, Snow, & Holzworth, 2011)		(Whish et al., 2005)
Bambatsi		Soybean	(Robertson & Carberry, 1998)
Barley	(Manschadi et al., 2006)	Stylo	(P. Carberry et al., 1996)
Broccoli	(Huth, Henderson, & Peake, 2009)	Sugarcane	(Keating, Robertson, Muchow, & Huth, 1999)
Butterfly pea		Sunflower	(Chapman, Hammer, & Meinke, 1993)
Canola	(Robertson, Holland, Kirkegaard, & Smith, 1999)	Sweet corn	(Henderson, 2011)
Centro		Sweet Sorghum	
Chickpea	(Robertson et al., 2002)	Vine	
Cotton	OZCOT:	Weed	
	(Hearn, 1994)	Wheat	(Brown et al., 2014)
Cowpea	(Adiku, Carberry, Rose, McCown, & Braddock, 1993)		Wheat (Wang et al., 2003)
Fababean	(Turpin et al., 2003)		NWheat (Keating, Meinke, Probert, Huth, & Hills, 2001)
Field pea	(Chen et al., 2008)		I_Wheat (Meinke, Hammer, van Keulen, & Rabbinge, 1998)
	(Robertson et al., 2002)		Nwheats (Asseng, Keating, et al., 1998)
French bean	(Henderson, 2011)	*Soil*	
GRASP	(Bell, Robertson, Revell, Lilley, & Moore, 2008)	DCD	(Cichota, Vogeler, Snow, & Shepperd, 2010)
	(Rickert, Stuth, & McKeon, 2000)	Erosion	(Freebairn, Silburn, & Loch, 1989)
Growth	*Eucalyptus species*		(Littleboy et al., 1992)
	(Huth, Carberry, Poulton, Brennan, & Keating, 2002)	Nitrogen (SoilN)	(Probert, Dimes, et al., 1998)
Lablab	(Hill, Robertson, Pengelly, Whitbread, & Hall, 2006)	Phosphorus	(Delve et al., 2009)

APSIM model	Origin/references	APSIM model	Origin/references
Lucerne	(Dolling, Robertson, Asseng, Ward, & Latta, 2005)	Pond	(Gaydon, Probert, Buresh, Meinke, & Timsina, 2012)
	(Probert, Robertson, et al., 1998)	Solute	(Paydar et al., 2005)
	(Verburg, Bond, Hirth, & Ridley, 2008)		(Poulton, Huth, & Carberry, 2005)
Lupin	(Farré, Robertson, Asseng, French, & Dracup, 2004)	Surface	(Connolly et al., 2001)
Maize	Origin: AUSIM-maize	Surface OM	(Probert, Dimes, et al., 1998)
	(Carberry & Abrecht, 1991)	SWIM	(Huth, Bristow, & Verburg, 2012)
Millet	(Van Oosterom, Carberry, Hargreaves, & O'leary, 2001)		(Connolly, Bell, Huth, Freebairn, & Thomas, 2002)
Mucuna	(Robertson, Sakala, Benson, & Shamudzarira, 2005)		(Verberg, Ross, & Bristow, 1996)
Mungbean	(Robertson et al., 2002)		(Verberg, Keating, et al., 1996)
Navybean	(Robertson et al., 2002)	Temperature	(Campbell, 1985)
Oats	(Peake, Whitbread, Davoren, Braun, & Limpus, 2008)	Water (SoilWat)	(Probert, Dimes, et al., 1998)
Oil Mallee			(Verberg & Bond, 2003)
Oil Palm	(Huth et al., 2012)	Water Supply	(Gaydon & Lisson, 2005)
Pasture	(Moore, Donnelly, & Freer, 1997)	*Animal*	
Peanut	(Hammer et al., 1995)	DDRules	
	(Robertson, Silim, Chauhan, & Ranganathan, 2001)	Graz	(Owens et al., 2009)
Pigeonpea	(Robertson, Carberry, Chauhan, Ranganathan, & O'leary, 2001)	Stock	(Freer, Moore, & Donnelly, 1997)
Potato	(Brown, Huth, & Holzworth, 2011)	*Climate*	
Rice	ORYZA:	Canopy	(Carberry, Adiku, McCown, & Keating, 1996)

APSIM model	Origin/references	APSIM model	Origin/references
	(Bouman & Van Laar, 2006)	E0	(Meinke, Carberry, Cleugh, Poulton, & Hargreaves, 2002)
	(D. Gaydon et al., 2012)	MicroClimate	(Snow & Huth, 2004)

According to Probert et al. (1995), the importance of long-term experiments lies in: 1) studying slow-effect treatments such as tillage, fertilisation on agricultural soil, 2) studying economic yield under successive climatic conditions and for several seasons, 3) reducing pilot error and increasing accuracy and 4) its unique results proving an important resource for evaluating the long-term performance of the target model. Accordingly, the performance of APSIM model (McCown et al., 1996) that operate on a daily timestep and CENTURY model (Parton et al., 1993) which operate on a monthly timestep, in simulating the soil processes and crop production for the long-term experiment (1969 - 1992) in Warwick - Queensland were investigated. Despite CENTURY's ability to predict relative yields, Probert et al. (1995) concluded that APSIM was more satisfactory in predicting absolute grain yield, soil-water, and drainage.

Carberry et al. (2002) and Carberry et al. (2009) used the data of over 700 commercial and experimental crops in all Australia cropping regions during the period 1992 to 2007 including barley, canola, chickpea, cotton, maize, mungbean, sorghum, sugarcane and wheat, to evaluate APSIM's performance validity in simulating yields. They concluded that APSIM is not only predictive of experimental (paddock) crops, but also of actual (commercial or farm) crops, where APSIM's crop yield results were close to experimental and farm crop yields. They also stressed that, to simulate any crop yields accurately, the precisely describe of soil resources (e.g. soil water, N), is essential in reducing the gap between the model and real results.

Recently, there has been considerable interest in using APSIM to: 1) simulate a range of crops, animals, soils and environments which represent the basis of any farm (Moeller et al., 2007; Williams et al., 2015) and 2) simulate crop development under different conditions of soil moisture, N, and fertility (Akponikpè et al., 2010; Asseng, Turner, & Keating, 2001).

APSIM simulation ability has been confirmed in the environments and farms of Australia (Asseng, Anderson, et al., 1998; Chenu et al., 2011; Peake, Robertson, et al., 2008; Peake, Gilmour, & Cooper, 2011), New Zealand (Moot, Hargreaves, Brown, & Teixeira, 2015), Asia (Gaydon et al., 2017), Europe (Asseng, Van Keulen, & Stol, 2000), India (Gaydon, Humphreys, & Eberbach, 2011; Mohanty et al., 2012), USA (Archontoulis, Miguez, & Moore, 2014), Africa (Micheni, Kihanda, Warren, & Probert, 2004) and China (Liu et al., 2012; Wang, Zheng, Yu, & Wang, 2007).

Most of the crop yield models applied in the Australian agricultural sector, including APSIM, do not explicitly account for: 1) inefficient use of water by most crops (Cornish & Murray, 1989; Hochman, Holzworth, & Hunt, 2009; Sadras & Angus, 2006) and 2) the typical constraints of Australian crop yield which involve pests, disease, weeds, low N availability (Angus & Van Herwaarden, 2001), phosphorus deficiency, sodicity, acidity, salinity, late sowing (Sadras & Angus, 2006), and harvest losses (Robertson, Carberry, & Lucy, 2000). As a consequence, there is a gap between modelled and farm yields (Mercau et al., 2007; Sadras, Baldock, Roget, & Rodriguez, 2003; Whish et al., 2005; Whish, Castor, & Carberry, 2007). However, Probert et al. (1995), Rykiel (1996), and Hunt and Boote (1998) found that model accuracy (model predicted outcomes aligning with the study context) could be achieved by feeding the model with sufficient, accurate and detailed data. Also, Carberry et al. (2002) and Carberry et al. (2009) stressed that, to simulate any crop yields, an accurate description of soil resources (soil water, N, etc.) is an essential requirement to reducing the gap between model and real results.

APSIM’s ability to simulate soil properties, management systems and environmental impact on crop characteristics has been confirmed in other studies such as Jones, Probert, Dalgliesh, and McCown (1996), Murray-Prior, Whish, Carberry, and Dalgleish (2005), Li et al. (2011), Dorey, Fournier, Lechaudel, and Tixier (2015), Ojeda, Caviglia, Irisarri, and Agnusdei (2018), Dias, Inman-Bamber, Bermejo, Sentelhas, and Christodoulou (2019), and Peng, Fu, Jiang, and Du (2020).

Furthermore, APSIM's validity has also been tested and confirmed for wheat and sorghum growth and grain yield under various conditions across Australia and the world, including different temperatures, N rates, water availability, sowing dates and CO_2 concentrations by many researchers such as MacCarthy, Sommer, and Vlek (2009), Chen, Wang, and Yu (2010), Lobell, Sibley, and Ortiz-Monasterio (2012) , Carberry et al. (2013), Sultan et al. (2014), Zhao et al. (2014), O'Leary et al. (2015), Ahmed et al. (2016), Chimonyo, Modi, and Mabhaudhi (2016), Liu et al. (2016), and Singh et al. (2017).

2.18.1 APSIM model description

APSIM consists of modules for soil, water, N, crop residue, and crop growth and development (Keating et al., 2003). Through its central control unit or engine, these modules can communicate and interact with each other to simulate agricultural systems options. To find out more about these modules and their mathematical basis as well as the source codes and more, go to www.apsim.info/documentation/.

2.18.1.1 Water module

SOILWAT (Probert, Dimes, et al., 1998) and SWIM (Verberg, Keating, et al., 1996; Verberg, Ross, et al., 1996) are the two modules of water balance and solute movement in APSIM. Although technically different, both are interchangeable and can handle all plant modules.

- **SOILWAT module**

SOILWAT is a cascading layer model originally derived from the precursors, CERES (Jones & Kiniry, 1986; Ritchie, 1972) and PERFECT (Littleboy, Silburn, Freebairn, Woodruff, & Hammer, 1989; Littleboy et al., 1992). It is a daily time-step module, so it requires the provision of daily climate data to successfully calculate an assortment process. The lower limit corresponding to a soil potential of 15 bar (LL15), drained upper limit (DUL) and saturated (SAT) volumetric water contents are employed to determine soil layers' water properties. Ordinarily, the soil profile may include more than ten layers with different thicknesses. Typically, the thickness of the upper layer ranges from 0.1 m to 0.15 m, while the lower layers may range from 0.3 m to 0.5 m. Layer width can also be determined by the user. With all modelled layers, precision is required as both the number of layers and their thickness influence experimental soil parameters. Crop, Residue, Solute, and SoilN are the APSIM modules that can communicate and interact with the SOILWAT module. The 'cascading bucket' which represents the long-term stored data of water pattern modules like WATBAL (Keig & McAlpine, 1969) and CERES (Jones & Kiniry, 1986; Ritchie, 1972) were adopted to build the evaporation, saturated and unsaturated water flow, solute movement, and runoff processes framework of the SOILWAT module.

For the implicit evaporation process, the modified motif of balance evaporation via Priestley and Taylor (1972) is the principle of the potential evapotranspiration calculation which represents the base evaporation value. Regarding the flow of saturated water; it takes place in any soil layer with the water content or soil water content (swcon) between the saturation boundary (SAT = top) and drained upper limit boundary (DUL = below), so a specific amount of the concerned layer water content will pass the DUL boundary to the subsequent layer. However, a flow of water may occur even though the layer is unsaturated (its swcon below the DUL point) in specific cases such as rainfall or evaporation events. In these like conditions, differences between soil layer water contents will be created, so the unsaturated water will flow either towards the surface or downwards. Unsaturated water flow is likely to occur within shallower soil layers and is unlikely to occur within deeper layers.

As regards to the movement of solutes, their calculation is fully correlated with the amount of water flowing within the saturated and unsaturated layers using a mixing algorithm concept. This algorithm assumes that most of the water travelling between layers is a mixture of completely dissolved substances. Consequently, the amount of transferred solutes between soil layers can be calculated from the total concentration within the flowing water. Rain runoff is calculated using the curve number runoff model procedure which was modified by the USDA for Soil Conservation Service (USDA, 1972). It includes the effects of previous soil water content and crop or crop residue which represent the soil cover and soil surface roughness due to tillage. Simply, this model estimates the runoff on a given day using the total amount of rainfall caused by storm/s that occur during that day using the following equation:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \quad \text{……………………………………… Equation 2-6}$$

Where:

Q = runoff (mm),
P = rainfall (mm), and
S = retention parameters (mm).

- **SWIM module**

SWIM are the initials of the package named Soil Water Infiltration Movement which was advanced by the Soils Department at CSIRO. It was adapted to simulate the movement of water during infiltration, evaporation and rediffusion in the soil. It uses the numerical solution of Richard’s and convection-dispersion (Verberg, Keating, et al., 1996; Verberg, Ross, et al., 1996) equations to shape solute movement. In APSIM, its application basically established on SWIM version No. 2.1 (Verberg, Ross, et al., 1996) and can operate independently of other software. The time steps for water motion in the soil layers are based on the bulk of water fluxes where large fluxes means less time to move. The moisture content with hydraulic conductivity and their correlation in each soil layer must be specified to this module to identify soil water parameters and characteristics. Surface roughness is taken into consideration when estimating runoff. Thus, preventing rain-water runoff may change over time depending on the soil surface topography. For example, it may decrease after tillage and may increase if the soil is bare, sealed or fallow. Therefore, soil with a sealed or crusted surface is treated as a thin, infinite membrane when estimating infiltration.

2.18.1.2 Crop module

APSIM has several programmed modules to simulate the impact of soil, climate and management conditions on pastures, forests, crop yield, and stages of growth and development. APSIM's potency is not limited to only one crop. It has the ability to simulate more than 20 different cropping system production and life plant cycle events through specialized modules that are installed within, including winter and summer cereals (Keating et al., 2003; Robertson et al., 2002).Thus, it has the ability to assess decisions made by farm administrators regarding the system of cultivation, irrigation, fertilisation, and crop sequence and planting time within the fixed or flexible rotations. To meet the requirements of this study, APSIM was built with the APSIM-Crop modules of Sorghum (Hammer & Muchow, 1991) and Wheat (Asseng, Anderson, et al., 1998; Asseng, Keating, et al., 1998).

- **APSIM-Sorghum module**

The QSORG (Hammer & Muchow, 1991) and AUSIM (Carberry & Abrecht, 1991) models both were the adopted basis in the APSIM-Sorghum module development.

Since then, and according to Wang et al. (2002), the sorghum module has been subject to considerable revision and development, and thus has recently been adopted as one of the crop module templates (CMT) of APSIM program. In this module, the growth of sorghum is fabricated in a daily time-step (on an area basis and not for solitary plants) which is totally dependent on the ready information regarding soil N, soil water supply, and climate provided from soilN, soilwat, meteorological or Met modules. To calculate the rates of runoff and freed vapour from a sorghum crop, the module returns the crop cover data to the soilwat module for this purpose. At the sorghum crop harvest stage, the sorghum and its root remains are pushed through the sorghum module to the residue and soilN module respectively, to simulate the soil condition. Start crop, transpiration, phenology, biomass accumulation, leaf area development, senescence, crop nitrogen, and finally the end crop are the nine successive phases of sorghum growth within the sorghum module, each of which is detailed in Figure 2-41 and listed in detail through the link on Appendix H.3.2.

- **APSIM-Wheat module**

The wheat module was derived mainly from a combination of Nwheat, which is a derivative of CERES-Wheat (Ritchie, Godwin, & Otter-Nacke, 1985) and I_wheat (Meinke, Hammer, van Keulen, Rabbinge, & Keating, 1997) procedures with some wheat approaches including Meinke et al. (1997), Meinke et al. (1998), Asseng, Anderson, et al. (1998), Asseng, Keating, et al. (1998), and Wang et al. (2003). Radiation, temperature and rain as the climatic factors, management practices and soil properties are fed on a daily basis to simulate wheat growth and development in this module. This module has recently been developed to simulate other cereal crops such as grain legumes and canola through a generic crop template and sharing a specific code (Wang et al., 2003). Thus, most of cereal crops' modular structure, constants and parameters are from external code (wheat.xml file).

The wheat module structure owns eleven key steps starting from the day of planting to the day of harvesting (Figure 2-42). The Phenology stage (third stage) has eleven growth stages including Sowing, Germination, Emergence, End of Juvenile, Floral Initiation, Anthesis, Start of Grain Filling, End of Grain Filling, Physiological Maturity, Harvest Ripe, and finally End of Crop. The beginning of each growth stage is determined by thermal time accumulation, excluding Sowing to Germination, which is determined by soil water content.

The duration of each thermal phenology phase can be specified according to these steps: 1) according to the phenology routines, the thermal time (tt) of each day is divided into eight 3-hours of air temperature, 2) according to the original routines in CERES-Wheat, the maximum and minimum crown temperatures (*Tcmax* and *Tcmin*) are calculated according to the maximum and minimum air temperatures (*Tmax* and *Tmin*), and correspond to air temperatures for non-freezing temperatures, 3) the average eight 3-hour crown temperature estimates (Δtt) will equal the daily value of thermal time (in degree-days) for that day and 4) the daily thermal time values will be cumulated into a thermal time sum (Thermal time target T) to determine the period length of each phase. Thermal time target (T) is specified by tt_<phase name> in wheat.xml. The steps of each stage are shown in Figure 2-42 and listed in detail through the link on Appendix H.3.2.

From this section, it can be concluded that deep ripping in the conservative farming system is one of the recommended solutions to alleviate soil compaction. However, its positive impact on soil structure is highly likely to diminish over time, in addition to depleting much of the tractor's power and fuel. Monitoring its long-term impact to make decisions regarding its adoption in the rainfed farm plan has become difficult as a result of deteriorating soil construction, especially for clay, due to extreme climate conditions such as minimal rainfall and elevated temperatures during the growing season. APSIM is the superior model for these circumstances. It could be used to assess the agricultural operation’s performance and farm management on the crop and soil components under long, contrasting climates, and thus contribute to decision-making. For more than 25 years, studies have shown the viability of APSIM and its ability to simulate various crops, soils and agricultural activities in the climates across Australia and the world. However, there is insufficient data to predict clayey crop production after deep tillage.

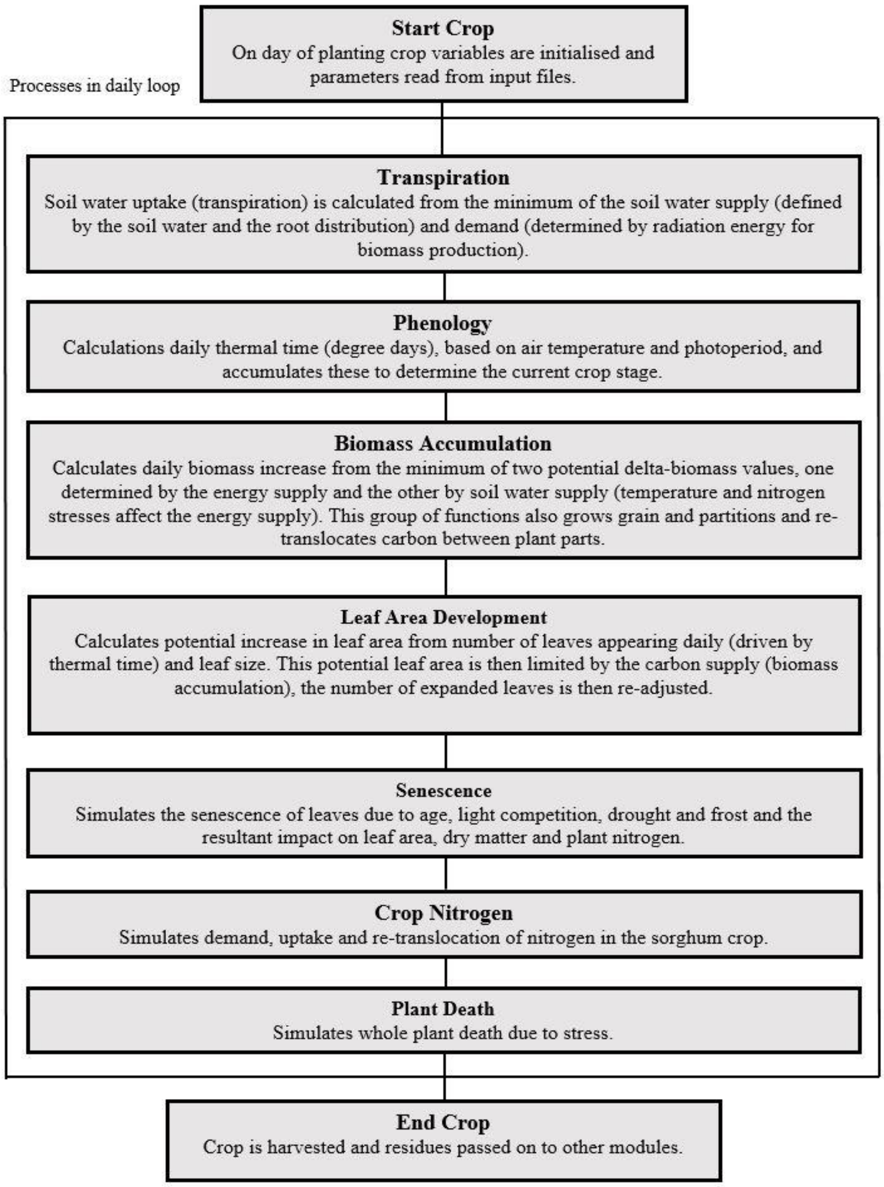

Figure 2-41: The key simulation steps order in the sorghum module (https://www.apsim.info/documentation/model-documentation/crop-module-documentation/sorghum/)

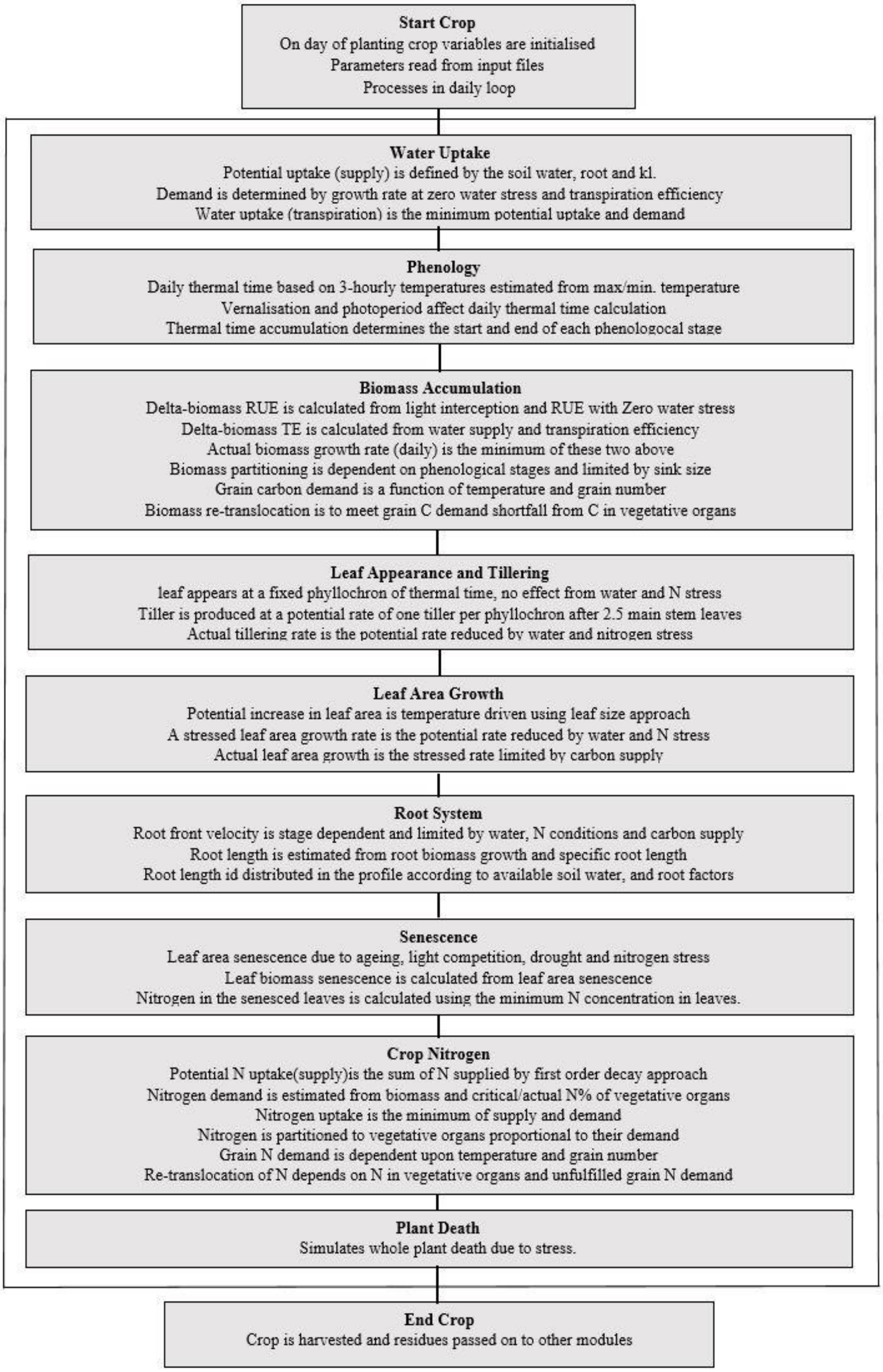

Figure 2-42 : the key simulation steps order in the Wheat module (https://www.apsim.info/documentation/model-documentation/crop-module-documentation/wheat/)

2.19 Conclusion

Like other developed countries, Australia strives to modernize the agricultural sector and increase its production to support the national economy and meet the global demand for food. Introducing new lands (horizontal expansion) and increasing existing lands' productivity (vertical expansion), are the global agricultural sector politics to meet the increasing demand for food as a result of the rapid population growth. The intensive and continuous cropping farming system along with fertiliser use, as well as the use of bulky and wider tractors, machines, and equipment with high capacities are the most current vertical expansion' techniques. Despite their success, with the climate deterioration, they have been diagnosed as one of the critical problems associated with organic matter depleted soils in recent years, namely soil compaction.

Compaction is the main reason for the deterioration of most arable soils' properties around the world and consequent poor yield, especially in soft and dense high clay content soils. Stakeholders agree that soil compaction will not be eliminated. Rather, it can only be mitigated and will therefore remain a feature of the world's modern agricultural system. Efforts have been made to devise solutions, and investigations are ongoing to determine which approach is better and more effective. Deep tillage is one of the solutions that many researchers have verified, and they have praised its efficiency through improving of both the compacted soils structure and crop yield.

Since not every system is free of negatives, deep ripping is characterised as costly and its beneficial impact does not last long, especially in clay soils. Correct design of the soil-penetrating plough parts plays a key role in reducing the requirements of pulling force, engine power, fuel consumption, thus making the practice less costly. Simplicity, comprehensiveness and generality are the G&O equation features that predict the forces affecting tillage equipment, resulting from interacting their working elements' geometry with soil conditions. And for this reason, G&O is a valuable tool for both designers, researchers and farmers.

Evaluating the performance of the crop/s system, farm operations, and their interactions under climate and soil conditions has become possible with APSIM, which has been widely confirmed as valid. With G&O and APSIM, the prediction of ripper tine draught force, appropriate tine, correct operational conditions, and its effect on the crop's performance under long-term climatic conditions, becomes easy.

Both models have a major impact on decision-making by farm management with regards to the adoption of deep tillage as a means of soil compaction mitigation. The technical and economical evaluation of deep tillage and its impact on the cereal crops components yield as well as verifying the validity of G&O and APSIM models in high clay content soils, however are very rare in Australia and especially Queensland. Thus, the literature study will guide this research in the development of appropriate recommendations that will support the Australian and Queensland agricultural sector.

3. DESIGN AND METHODOLOGY

This chapter outlines the experimental design and methodology components of the dissertation. It outlines details of the experimental design and field assessment for deep ripping trials and G&O modelling investigations. This chapter also addresses the use of the APSIM to simulate the conducted experiments' conditions in both locations and predict the productivity of the studied soils.

3.1 Evaluation of deep tillage systems' impact on soils and crops, and benefits at two Queensland farms with high clay content soil

This section considers the design and methodology for the field-assessment component of the dissertation.

3.1.1 Site description

In this study, two sites were dedicated to assessing deep ripping, the first site was located at the agricultural field station (Agricultural plot (Ag plot) of the University of Southern Queensland (USQ), Toowoomba, Darling Downs, Queensland, 4350, Australia, (27˚36'36.25"S 151°55'49.54"E) during 2016 - 2017, which is displayed in Figure 3-1. According to the key soil orders, the site's soil is classified as a Red Ferrosol (Isbell, 2016). According to Gee and Bauder (1986), soil textural analysis (via the Pipet method) for the bulked 0 mm -800 mm layer was 69.06 % clay, 10 % silt and 20.94% sand, with < 0.8% slope which is considered common to most of Queensland. The site was planted with a wheat crop during June 2015 and harvested in November 2015. This was followed by sorghum cultivation and harvest in April 2016. Total rain and average maximum temperatures were obtained from a weather station adjacent to the field. The monthly readings are displayed in Table 3-1.

The second study location was at Evanslea in the Toowoomba Region, Queensland, 4356, Australia, (27˚31'25.44" S 151˚31'31.26" E) during 2017 - 2018, as shown in Figure 3-2. The soil classification at this site is Black Vertosol (Roberton, 2015). Through the Gee and Bauder (1986) soil textural analysis (via the Pipet method) procedure, the soil texture of 0 mm -800 mm layer was 64.79% clay, 23.44% silt and 11.77% sand. The site was planted with a sorghum crop during October 2015 and then wheat

Figure 3-1: Ag plot site, University of Southern Queensland - Toowoomba, QLD (Google Earth, 2016)

Table 3-1: Total rain and average of maximum temperature from Ag plot - USQ weather station

Climate data	2016		2017											
	Nov.	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
Av. TMax (C^o)	30.8	33.3	33.9	34.7	29.2	24.1	22.6	20.4	20.3	19.7	24.3	23.1	23.2	27.2
Tot. Rain (mm)	21.1	22.9	71.8	45.8	328.7	14.1	12.6	28.5	43.4	4.3	5.4	167	36.6	82.6

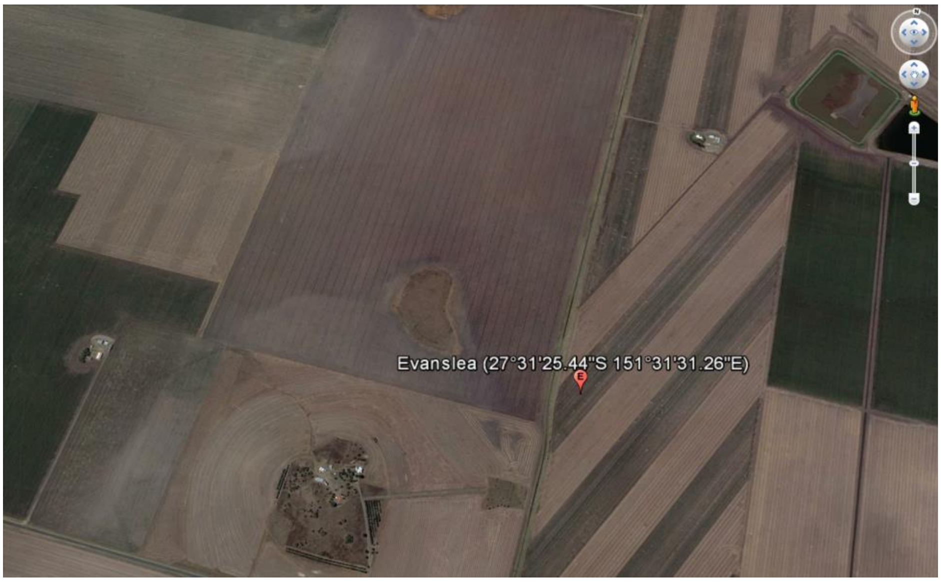

Figure 3-2: Evanslea site - Toowoomba, QLD (Google Earth, 2016)

Table 3-2: Total rain and average of maximum temperature from Evanslea' weather station

Climate data	2017				2018		
	Sep.	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*March*
Av. TMax (C^0)	28.0	27.2	28.9	32.8	34.5	31.9	30.1
Total Rain (mm)	0.3	85.4	8.2	90.3	17.7	90.9	22.8

in June 2016. After that, the site left was left fallow until November 2017 when it was planted with sorghum again (A. Ruhle, personal communication, April 24, 2018). Total rain and average maximum temperatures were obtained from a weather station situated on the farm. The monthly readings are displayed in Table 3-2. Soil at both sites have a high percentage of clay, which encouraged their selection for this study.

3.1.2 Experimental design

For the first location study (Ag plot, USQ), the experiment was carried out in a split plot with a completely randomized block design in three replicates (3 × 3 × 2). The experiment consisted of three blocks (as replicates), each block (5 m × 82 m) divided into three plots representing three levels of deep ripping (D1= 0 - 0.3 m, D2= 0 - 0.6 m, and control (C= no ripping). The whole plot (5 m × 25 m) was divided into two sub-plots representing two levels of N fertiliser rate as urea 46% N (with fertiliser (N= 140 kg/ha (as 304 kg urea/ha) and N= 110 kg/ha (as 239 kg urea/ha) after sorghum and wheat sowing respectively) and without urea 46% N fertiliser (N= 0 kg urea/ha)). The treatments were randomly distributed to 18 experimental units to avoid introducing bias into the results. To ensure: 1) the stability of the machinery unit (tractor + ripper) before the beginning of each treatment and 2) there was no overlap between the treatments along the experiment time (short term), a buffer of 5 m in width and 3.5 m in length was used between plots. The layout of the experimental design is visually represented in Figure 3-3.

For the Evanslea site, the experiment was designed in a completely randomized block design with three replicates (3 × 3). The experiment consisted of three blocks (as replicates), each block (12 m × 350 m)) divided into three plots (plot = 12 m × 100 m) representing three levels of deep ripping (D1= 0 - 0.3 m, D2= 0 - 0.6 m, and control (C= no ripping). As with the Ag plot design, treatments were distributed randomly to the nine experimental units to reduce the chances of introducing bias into the results. As with the Ag plot, a buffer with 25 m in length and 12 m in width was used to

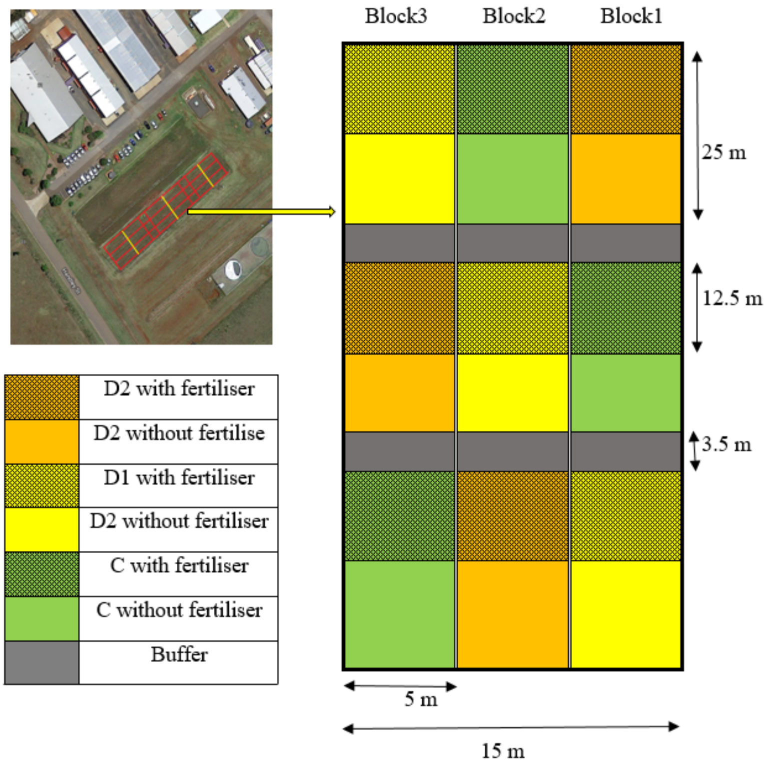

Figure 3-3: Ag plot site, USQ layout of experimental blocks, treatments plots and treatments sup-plots

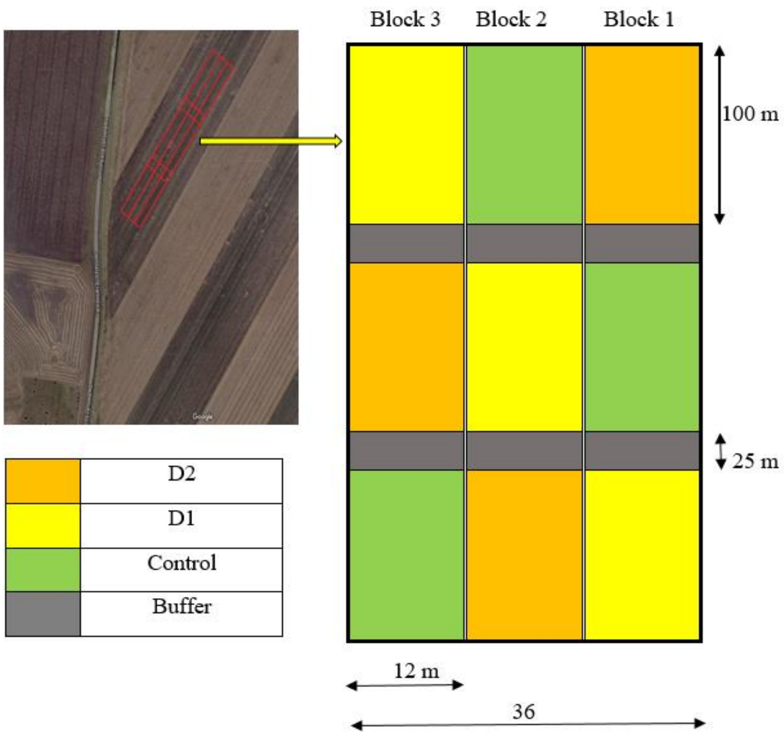

Figure 3-4: Evanslea site layout of experimental blocks and treatments plots

separate the treatments to ensure the stability of the tractor and subsoiler at the beginning of each plot during the application of the experiment and to prevent future interference between the treatments. The experimental layout design is visually represented in Figure 3-4. There was no fertiliser rate at this site as the randomly ripped and neutral (control) plots were under the regular farmer practice.

3.1.3 Materials used

At both sites, various tractors, devices, equipment and tools were used before, after and during the deep ripping application. These are summarised in Table 3-3.

Table 3-3: Materials used at Ag plot, USQ and Evanslea sites

Materials	Ag plot	Evanslea
Tractor/s	JD 6150 M and 6105 M, Belarus 920 and New Holland T6.150	JD7920, 8400 and 8310 RT
Ripper	Barrow single tine	Tilco Eight Tines
Harrow	Maschio rotary hoe FRESA B 205	N/A
Planter/Seeder	Nodet Gougis Pneumasem II (Pneumatic) (Sorghum) & BIG RIG seeder (Wheat)	MaxEmergePlus - JD (Pneumatic) (Sorghum)
Laboratory thresher	WINTERSTEIGER LD 350	=
Penetrometer	Rimik CP40II cone penetrometer	=
Pull meter	-	-
Data logger	Rimik Digital Data-Node	=
Snatch strap	Ridge Ryder, 4WD – 15000 KG	=
Post driver (insertor)	Portable Christie's Engineering CHPD78	=
Lubricant spray	Boston 400 g	=
Core tubes	-	-
Extractor (lifter)	-	-
Scraper	Rhino Black 100 mm scraper	=
Table	Lifetime 6 ft bi-fold blow mould trestle	=
Oven	Steridium, 800 L chamber capacities	=
Flags	Hand-made	=
Sand bags	Synthetic woven sand bag - 0.8 m x 0.4 m	=
Chicken bags	Chicken bags SM foil 213×165×58 mm	=
Measuring tape	100 m and 8 m	=
Balance	HYPROP - Max 2200 g	=
Balance	KERN & SOHN - Max 35 Kg	=
Bird netting	Diamond econetting 4 m x 25 m x 0.005 m white anti-bird net	N/A
Scarecrow	Hand-made	N/A
Secateurs	Hortex 205 mm heavy duty bypass pruner	=
Videotapes	-	N/A
Steel posts	EuroSteel 1.65 m Black Y Post	N/A
Foil containers	Rectangular aluminum trays 150×75×51 mm	=
Stakes	Gardman 12 x 12 x 600 mm hardwood garden stake	=

Materials	Ag plot	Evanslea
Netting bags	Red Seal netting bags 0.5 m	N/A
Plastic bags	Plain LDPE 35 UM plain 330 x 230 mm	=
Hammer	Craftright 1.8 kg sledge hammer	=
Gloves	Rhino Goflex gloves	=
Storage container	The Award 50 litre plastic storage container with lid and 4 wheels	=

Note: same (=), locally made (-), and not applied (N/A)

3.1.4 Tractor and ripper (machinery unit) used

To assess the deep ripping operation's effect on some clay soil and crop parameters, a single tine ripper (Barrow *subsoiler*), with straight shank 0.04 m in width, 0.095 m wide foot (tip), 35˚ rake angle (tip) and 0.7 m maximum depth, was connected to the John Deere (JD) 6150 M tractor with three-point linkage (Figure 3-5) to rip the Ag plot, USQ location. To assess the deep tillage operation, the effect of ripping on the Red Ferrosol soil and the planted crops (sorghum and wheat) was monitored during the 2015/16 and 2016/17 seasons (short-term).

Figure 3-5: Machinery unit (JD 6150 M with Barrow single tine ripper) during ripping operation at Ag plot site, Toowoomba

At the Evanslea site, a ripper with foldable-single bar frame and eight, steel, adjustable, and straight Tilco tines, was mounted on a JD 7920 tractor with a three-point linkage to rip the site soil in this study (Figure 3-6). The tines were distributed on the folding frame in 1.5 m spacing, so the operating width for the ripper was 12 m. To assess the deep ripping operation, the effect of ripping on the characteristics of the

Vertosol clay soil and the planted crop (sorghum) was monitored for one season 2017/18 (short-term).

Figure 3-6: Machinery unit (JD 7920 with 8 tines TILCO ripper) during ripping operation at Evanslea site, Toowoomba

3.1.5 Tractors and rippers used for draft force measurement

At the Ag plot site, two tractors, ahead (driver) and neutral (driven) with pull meter and its accessories were used to measure ripper draught force. The JD 6150 M represented the ahead (driver) tractor while the Belarus 920 tractor represented the neutral (driven). Figure 3-7 shows the connection arrangement of the ripper, pull meter and tractors during the procedure.

Figure 3-7: JD 6150 M, pull meter, Belarus 920, and Barrow single tine ripper (respectively) during the draft force procedure, Ag plot site

At the Evanslea site, the Ag plot site arrangement was used to measure ripper draft force under the same working depths, but a different tractor and ripper was used. Two tractors were used. The JD 7920 represented the neutral (driven) and carried the Tilco eight tines ripper, while the ahead (driver) tractor was JD 8310 RT where the pull meter was attached to its drawbar. The strap connected the other pull meter side to the front of the JD 7920 (Figure 3-8).

Figure 3-8: JD 8310 RT, pull meter, JD 7920 and Tilco eight tines ripper (respectively) during the draft force procedure, Evanslea

3.1.6 Seed drill, planter and adding rate used

At the Ag plot site during the summer season (first season), the sorghum (*Elite Mr Buster*) provided by the Pacific Seeds Company (Toowoomba), was planted on 21 December 2016. According to Pacific Seeds Company via an information label on sealed sorghum bag, the minimum germination, purity and maximum other seeds, and inert matter are 85%, 99%, 0.1%, and 0.5%, respectively. The adding rate was 3 kg/ha according to the DAF (2011) recommendation for the dryland system. The ***Nodet Gougis Pneumasem II*** pneumatic precision with Belarus 920 tractor (Figure 3-9) was used to plant the sorghum seeds in four rows with 0.9 m spacing. Prior to planting, the planter was calibrated to place the recommended sorghum seed amount per hectare (of 3 kg/ha (81000 seed/ha)) using the ASABE (2002) procedure.

At the same location during the winter season (06 July 2017), a winter crop was planted. The Spitfire wheat cultivar with 90% germination rate was provided and drilled by the Leslie Research Facility - Institute for Agriculture and the Environment.

The Big Rig seeder (Australian designed and manufactured) and New Holland T6.150 tractor (Figure 3-10) were used to sowing the wheat seeds in nine rows with 0.25 m rows spacing. An email (J. Sheedy, personal communication, July 6, 2017) confirmed that the seeder was calibrated by Leslie Research to place 46 kg/ha, which represented the farmer practice.

Figure 3-9: Machinery unit (Belarus 920 tractor with Nodet Gougis Pneeumasem II planter) during sorghum planting operation at Ag plot site

Figure 3-10: Machinery unit (New Holland T6.150 with Big Rig seeder) during wheat sowing operation at Ag plot site

At the second location (Evanslea site (commercial field)), the *Elite Mr Buster* sorghum cultivar was planted on 04 November 2018, which was considered early planting for the summer season. At this site, the sorghum cultivation and its post-cultivation service operations were carried out by the farmer's own tractors, equipment and operators according to his practice.

Mr Buster was applied in sixteen (16) rows with 0.75 m spacing by the MaxEmergePlus pneumatic planter (manufactured by JD Company) (Figure 3-11). A. Ruhle (personal communication, November 18, 2017) stated that prior to sorghum planting, Anhydrous Ammonia (NH_3 with 82% N as a liquefied gas) was applied in rate of 100 kg of actual N per hectare (= ~ 122 kg/ha), while 15 liters per hectare of Yara Flowphos 13Z (liquid fertiliser with 9% N, 1% K, 13.5% P, and 0.9% Zn) diluted with water (1:3) was injected during sorghum planting. In the same letter, Andrew stated that the sorghum planting rate was 70000 seeds/ha (2.6 kg/ha).

Figure 3-11: Machinery unit (JD 8310 RT with MaxEmergePlus pneumatic planter) during sorghum planting operation at Evanslea site

3.1.7 Field application of methodology

3.1.7.1 Ag plot site

After dividing the experiment field as shown in Figure 3-3 and before ripping, on 20 November 2016, a mounted Rimik CP40II cone penetrometer on constant drive device with soil sampling kit were used to measure soil strength, soil bulk density and soil water content before ripping for the first time. Along the plot width (5 m), the penetrometer's trolley passed twice. In each pass, the penetrometer's trolley stopped four times at a one-meter distance and the trolley bar penetrate to 0.70 m in depth to record soil penetration resistance. Followed by and close to first and third penetrating spot for the first pass and second and fourth penetrating spot for the second pass, a hollow tube was pushed by vibration to the same depth and then lifted to pull soil samples to determine the soil bulk density (Figure 3-12). During this process, the field with its plots received 72 penetrating spots and 36 pushing hollow tubes. These readings were averaged to find average bulk density, moisture content and soil strength for the whole field treatment at a depth of 0 - 0.75 m before ripping. This data was collected to use for parameter comparison after ripping. One day after sampling on 21 November 2016, the Barrow single tine ripper was attached to the JD 6150 M tractor, as shown in Figure 3-5, to rip the soil at two depth levels (D1 = 0 - 0.3 m and D2 = 0 - 0.6 m) and according to the experiment design (Figure 3-3), while the control plots were left without ripping (Figure 3-13). Using the JD auto-steering technology, the field was ripped at 1 m spacing.

Figure 3-12: Ag plot site: (A) Recording soil penetration resistance, (B) Pulling soil bulk density tube, (C) Soil bulk density samples dividing (first time)

The draft force is an important parameter in this study, so after ripping the soil near the experiment field, the pull meter was used to measure the ripper pulling force. The arrangement of tractors and the pull meter during this operation is shown in Figure 3-7. Along a 100 m and a 75 m cross-section, the tractors were passed nine times (six times to calculate the draught force under two ripping depths (3×2), while the other three times were to measure the rolling resistance (3×1) by lowering the tine to nearly touching the ground (but not inserted) in a completely randomized block design.

The field was harrowed after ripping to produce finer soil particles suitable for seed growth using the Rotary Hoe Maschio FRESA B 205 with JD 6105 M tractor (Figure 3-14). This process was conducted across all experiment plots, including the control on 21 December 2016.

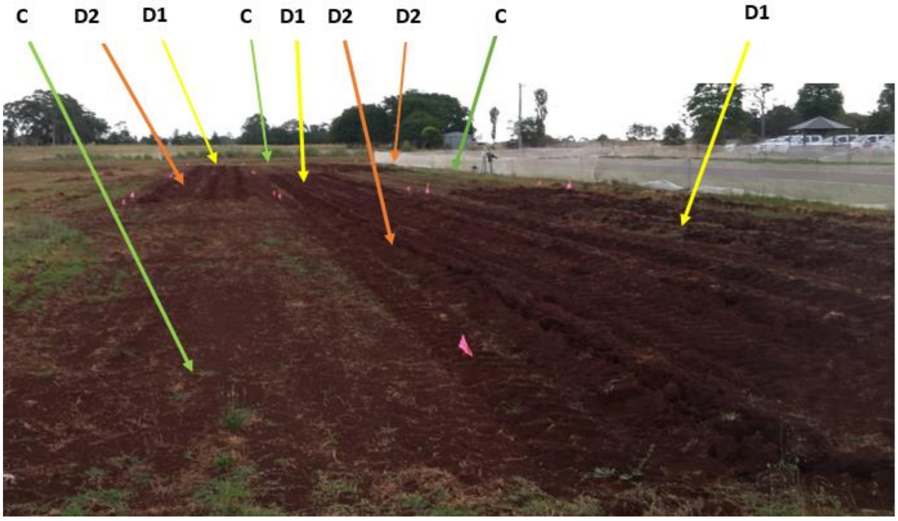

Figure 3-13: Ag plot site: After ripping (C = control (no ripping, green arrows), D1 = level one of deep ripping (0 - 0.3 m, yellow arrows) and D2 = level two of deep ripping (0 - 0.6 m, brown arrows)

Figure 3-14: Machinery unit (JD 6105 M with Maschio FRESA B 205 rotary hoe) before softening the Ag plot soil surface

After harrowing, the Belarus 920 tractor with a locally made rectangular frame leveller (3.1×1.65 m) was used to level the soil surface. Next, same Belarus 920 tractor with Nodet Gougis Pneeumasem II planter) was used to plant the sorghum (*Elite Mr Buster*) in four rows at 0.9 m spacing with seed spacing of 0.14 m (Figure 3-9). Then the sprinkler irrigation system, which consisted of two main pipes and 9 spray heads for each main pipe, was installed for supplementary irrigation (Figure 3-15). Two irrigation events took place during the season. These occurred: 1) after sowing event, and 2) in season.

Figure 3-15: Ag plot: Sprinkler system irrigation after sorghum sowing

The second factor studied was the fertiliser rate. Urea 46% N fertiliser was used and applied at two rates. 140 kg N/ha (as 304 kg urea 46% N /ha) was the first rate which was the optimum rate used in a study conducted by Hussein et al. (2017); Hussein (2018), while no fertiliser was the second treatment rate. During an interview, D.L. Antille (personal communication, November 23, 2016) stated that the best time to add fertiliser is after 30 days of planting when most plants will have five to six leaves. Standard agronomic practice also considers this to be the best time to add fertiliser (Gerik, Bean, & Vanderlip, 2003). Four trenches (12.5 m in length) parallel to the four sorghum rows were excavated to a depth of 0.05 m and 0.08 m away from the sorghum row. The urea 46% N (342 g/12.5m) calculated on the fertiliser's recommended quantity and the number of cultivation rows number per hectare, was added to each sorghum row manually on 21 January 2017: trenches were dug, fertiliser was added and the soil was re-placed (Figure 3-16).

One of the problems encountered and documented by researchers at this site was early growth being eaten by ducks, kangaroos and rabbits. To avoid this problem, and to maintain the plants' integrity, the field was surrounded with bird netting on 25 January 2017; thus, overcoming the problem (Figure 3-17). Despite the netting installation, the field was monitored daily by taking photographs and recording any situation requiring follow-up.

Figure 3-16: Ag plot site: Four trenches (12.5 m) parallel to the four sorghum rows with urea 46% N

Figure 3-17: Ag plot site: Bird netting installation to prevent animals eating crop

After nearly three months of deep tillage with the sorghum at fifty-two days of growth, a mounted Rimik CP40II cone penetrometer and soil sampling kit were used to monitor soil strength, soil bulk density and soil water content on 23 February 2017 (second time). The first used procedure was repeated and the penetration and bulk density results (72 and 36 for penetration and soil bulk density respectively) were averaged to calculate average bulk density, moisture content and soil strength for the field treatments to a depth of 0 - 0.75 m after ripping.

Most of the cereal crop, especially in its grain formation stage, was observed (by the researchers) to have been exposed to consumption by birds, in particular parrots. Basing on these observations, and during the sorghum stages between the soft-dough stage and hard-dough stage where about three - fourths of the grain weight has accumulated (Vanderlip, 1972), and to scare birds away from the crop and to keep the heads safety, the videotapes (above the field) and scarecrows (across the field) were installed while the heads for 4 m of the middle four rows were covered by the red netting bags (onion bags) on 27, 28, and 29 March 2017 (Figure 3-18). These precautions were taken after discussion and consultation with the supervision team.

Figure 3-18: Ag plot site: Red netting bags (onion bags), videotapes, and scarecrows to scare birds and protect sorghum heads

After nearly a month of preventive action, on 24 April 2017, nine samples (approximately 150 - 200 g per sample) were randomly separated and collected from six to eight heads, and placed in an oven at 130˚C for 18 hours according to the ASABE (1988) procedure to determine the gravimetric moisture content, hence the sorghum readiness for harvesting (moisture content less than 25 - 30% (D.L. Antille, personal communication, April 21, 2017)). The seed moisture content was then calculated using the Simonyan, El-Okene, and Yiljep (2007) equation (3-1) on wet weight basis.

$$MC_{wb} = ((W_i - W_d) / W_i) \times 100 \quad \text{Equation 3-1}$$

Where:

MC_{wb} = moisture content, wet basis (%),

W_i = initial sample weight (kg or g) and
W_d = dried sample weight (kg or g).

The above-ground plant biomass measurement is considered a reliable and fairly accurate indicator of crop productivity and performance (Freeman et al., 2007). When the grains reached the optimum moisture for harvesting, the biomass was measured using the direct sampling method (weigh the actual biomass of plants 1 m per row). Thus, after onion bags removal (Figure 3-19, A), plants of the one meter from the four meters covered heads and for the four rows per plot, were allocated to hand-cutting at approximately 0.02 m above the ground on 06 May 2017 (Figure 3-19, B). The collected plants were placed in the oven at 65˚C for at least 72 h which is considered sufficient to reach a stable weight and dry mass (Jackson, Farrington, & Henderson, 1986). The results represented the dry biomass for this specific area (Equation 3-4). After, the dry biomass for a hectare was then derived.

At the same time, the onion bags were removed from the heads of the remaining three meters of the four covered rows were harvested manually (using the secateurs) and placed in sand bags (Figure 3-19, C). Finally, according to D.L. Antilles' email (personal communication, April 21, 2017), the sand bags of heads were dried at 60˚C for one day to reach the correct threshing and storage moisture range (8.89 -16.5% wb) (Simonyan et al., 2007).

Figure 3-19: Ag plot site: Sorghum biomass and harvesting process: (A) Red onion bags removal, (B) Biomass collecting, (C) manual heads cutting and packing in sandbags (harvesting)

Through collaboration between CSIRO Agriculture & Food (CSIRO AF) and D.L. Antille, the laboratory thresher WINTERSTEIGER LD 350 was used to thresh, de-awn and clean the sorghum seeds (Figure 3-20, A). After threshing and yield calculation, six random samples of threshed sorghum grains (100-150 g) representing the experiment treatments (D1-0, D1-140, D2-0, D2-140, C-0, and C-140) were prepared, weighed and dried at 100˚C for 40 hours (D.L. Antille, personal communication, May 31, 2017). The aim was to determine the harvested seeds' moisture content and then correct them according to the standard moisture for commercialization of sorghum grain which is 13.5% (GTA, 2015).

Figure 3-20: Threshing, de-awning, and cleaning crop seeds at CSIRO AF Organization, Toowoomba

As planned, the next step was to prepare the wheat field (winter season). All remaining heads were removed manually from the sorghum crop and the sprinkler irrigation system pipes were lifted. Next, plots were shallow deep rotary-hoed with the JD 6115 R, 2.55 m in width with Maschio FRESA B 205 rotary hoe 2.08 m in width at an average speed of 13 km/h to cut, chop and mix the trash and crop residue with the soil on 30 May 2017 (Appendix A.1.1).

Five weeks later, on 06 July 2017, the tractor (NH T6.150) and 3-point linkage mounted seeder (Big Rig (Australian designed and manufactured)) from the Leslie Research Facility, was used to plant wheat (*Spitfire*) in nine rows with 0.25 m space between the rows, and 2 m in total with seed spacing (intra-row) of 0.04 m (Figure 3-

10 & Appendix A.1.2). The seeder nine dual disc furrow opener distributed among two rows (five on the front row and four on the rear row) which calibrated to place 46 kg/ha (J. Sheedy, personal communication, July 6, 2017). The next day, the bird netting and sprinkler irrigation system (two main pipes and nine spray heads for each main pipe) were re-installed (Appendix A.1.3). Due to adequate rainfall, the sprinkler irrigation system was not operated after wheat planting, so during this season, the field was irrigated twice: 1) after fertilising event and 2) during the growing season. After a week, the seedlings gradually began to emerge and the previous seedling safety procedure was followed. The videotapes and scarecrows were re-installed to scare the ducks and other birds away from the young seedlings (Appendix A.1.4).

During the wheat season, the sorghum season activities and measurements were repeated. Table 3-4 summarises these activities and measurements at the Ag plot site.

Table 3-4: Activities and measurements during wheat season at Ag plot site

Date	Activity or Measurement Details
12/08/2017	At the beginning of the tillering-Feekes 2.0 stage, urea 46% N fertiliser was added at rate of 110 kg N/ha (as 239 kg urea 46% N /ha); the optimum rate found by Hussein et al. (2017); Hussein (2018). The time of fertilising was selected according to Miller (1999) recommendations, who stated that the number of wheat heads per square may increase as a result of increasing tillering rate when N is applied during the tillering stage. In addition, the temperature during this month was low (19.7˚C, Table 3-1), which encouraged the fertilisation and helped the plants avoid problems including winterkill, foliar fungal disease and aphid injury (Miller, 1999). Nine trenches (12.5 m in length) parallel to the wheat rows were dug (Appendix A.1.5). According to calculations, depending on the recommended quantity of fertiliser and the number of cultivation rows per hectare, the 46% N urea was 75 g/12.5 m.
21/08/2017	A Rimik CP40II cone penetrometer and soil sampling kit were used to monitor soil strength (cone index), soil bulk density and soilwater content after ripping (third time). The sorghum season procedure (first time (before ripping) and second time (after ripping)) was used in this objective.
17/11/2017	Checking the wheat readiness for harvest with the sorghum procedure where nine samples (150-200 g) were dried for 18 h at 130˚C according to the ASABE (1988) procedure and

Date	Activity or Measurement Details
	the Simonyan et al. (2007) Equation (3-1) was used to calculate the moisture content on the wet weight basis (wb).
25/11/2017	Measuring the above-ground wheat dry biomass during the wheat mature and harvest-ready-Feekes 11.4 stage (Miller, 1999) at approximately 20 mm above the soil surface of one meter. Four rows (2, 4, 6, and 8) out of nine were cut. The sorghum procedure regarding drying time for (72 h) and temperature degree at (65 ˚C) was used in this process (Appendix A.1.6).
26/11/2017	Next day, the whole plant of three meter from the middle five rows (3, 4, 5, 6, and 7) out of nine were manually harvested and then placed in sand bags. Grains were dried at 60˚C for 24 h to reach the grain threshing and storage moisture range.
05/01/2018	Wheat seeds threshed, de-awned and cleaned through (CSIRO AF) WINTERSTEIGER LD 350 laboratory thresher (Figure 3-20, B).
07/01/2018	Six random samples of threshed wheat grains (100-150 g) representing trial treatment were dried at 100˚C for 40 h to the correct yield moisture according to the standard moisture for commercialization of wheat grain which is 12.5% (GTA, 2017).
01/03/2018	A Rimik CP40II cone penetrometer with soil sampling kit were used to monitor soil strength, dry bulk density and water content after ripping (fourth time). The first (before ripping), second (after ripping), and third (after ripping) sorghum procedures were used in this objective.

3.1.7.2 Evanslea site

At this site, another type of soil was incorporated to broaden the research scope. Queensland has a large area of Vertosols (Dalal, 1990) with high clay content (40-80 g /100 g) (Hulugalle & Scott, 2008). It is used for cereal, cotton, and dairying production (Hulugalle & Scott, 2008; Martin & Cox, 1956). For these reasons and more, efforts were united to obtain an approval for the deep ripping experiment at one farm with Vertosols. The Evanslea site has a black Vertosol with a high clay content (64.79 g /100 g). It is a commercial farm subjected to controlled traffic. After obtaining the approval of the farm owner Andrew Ruhle, the experiment was designed. The design was somewhat similar to the design of the Ag plot station site, but there was no fertiliser treatment and the area of blocks with plots was larger (Figure 3-4). Activity during the sorghum season (wet-season) is summarised in Table 3-5.

Table 3-5: Activities and measurements during sorghum season, Evanslea site

Date	Activity or Measurement Details
01/09/2017	The experiment field was divided according to the pre-set design (Figure 3-4).
07/09/2017	After division, and before ripping, a Rimik CP40II cone penetrometer with soil sampling kit were used to measure soil strength, dry bulk density and soil water content before ripping (first time) (Appendix A.2.1). In almost the middle of the plot length and along its width (12 m), the penetrometer's trolley passed once. In this pass, it stopped five times in the 3 m distance and the trolley bar penetrated the soil to 0.70 m in depth to record penetration resistance. During the same pass, and close to the bar' cone holes, a hollow tube was pushed by vibration and lifted three times to the same penetrometer depth to determine soil bulk density and water content. Then, the 45 penetration spots (3×5×3) with 27 pushing hollow tube readings (3×3×3) were averaged to determine the state of the field experiment prior to deep ripping regarding soil strength, bulk density and moisture content.
07/09/2018	A single, foldable ripper frame bar with eight, steel, adjustable, straight Tilco tines distributed on the folding frame in 1.5 m spacing, was mounted on the JD 7920 tractor with its three-point linkage to rip the site soil to two depth levels (D1=0-0.3 m and D2=0-0.6 m) according to the experiment design, while the control plots were left unripped (Figures 3-6 & 3-21)
07/09/2018	Near the ripping experiment field, the JD 7920 (the neutral (driven) tractor) with Tilco ripper was towed by the JD 8310 RT (ahead (driver) tractor) to measure the Tilco ripper draft force with a pullmeter device which mediate the two tractors. The Ag plot draft force and rolling resistance procedure was used at the Evanslea site (Figure 3-8).
10/09/2017	After three days of the ripping experiment, and at the mid-length of ripping plots, eight tillage line traces were marked by eight numbered flags to make them very clear. Five locations were similarly elected and marked along the width of each non-ripping plot. Close to the flags, penetration resistance, soil bulk density and soil moisture content were monitored throughout the 2017/18 sorghum season (Appendix A.2.2).

Date	Activity or Measurement Details
04/11/2017	A Rimik CP40II cone penetrometer with soil sampling kit were used to monitor soil strength, soil bulk density and soil water content after ripping (second time). For control (non-ripping) plots and near the flags location, same procedure was repeated, but with four bulk density sampling tubes. These three plots received 15 penetrating spots (3×5) with 12 pushing hollow tubes (3×4). With regard to the ripping plots, the penetration device dropped its cone bar eight times near the indicator flags that extended along the plot width, while the hollow tube penetrated the soil four times near the cone holes. Thus, D1 and D2 plots received 48 penetrating spots (3×8×2) with 24 pushing hollow tubes (3×4×2). In total, the whole field received 63 penetrating spots with 36 soil sampling tubes. The readings were averaged to determine the state of the field experiment treatments after deep ripping regarding soil bulk density, moisture content and strength (cone index).
04/11/2017	The JD pneumatic planter, *MaxEmergePlus*, was pulled by the JD 8310 RT to plant sorghum (*Elite Mr Buster)* in sixteen (16) rows with 0.75 m spacing and seed spacing (intra-row) of 0.02 (Figure 3-11).
18/01/2018	During a routine field inspection, an obvious difference in growth was observed between the D1, D2 and control plants (Figure 3-22).
04/03/2018	A. Ruhle (personal communication, March 04, 2018) mentioned that the sorghum would be harvested on 07 March 2018. On this day, when the sorghum reached four months age, the above-ground sorghum biomass was taken (Appendix A.2.3). As the sorghum lines number was somewhat large, a sample representative of the biomass lines of the whole treatment plot was taken. First, for the first replicate of the C, D1 and D2 treatments, the 1 m of sorghum from five lines (2, 5, 8, 11, and 14) were cut. Second, 1 m of sorghum from five lines (3, 6, 9, 12, and 15) were cut for the second replicate of the C, D1 and D2 treatments. Third, for the C, D1 and D2 third replicate, 1 m of sorghum from five lines (2, 5, 8, 11, and 14) were cut. Finally, the Ag plot site drying procedure time (72 h) temperature (65˚C) were used.
04/03/2018	On the same day, the sorghum was harvested manually, and the same biomass strategy was used where for the first replicate and all treatments, the sorghum heads of three meters for the lines (2, 5, 8, 11, and 14) were cut. Then, for the second replicate for all treatments the sorghum heads of three meters for the lines (3, 6, 9, 12, and 15) were cut and the same for the third replicate. Then the heads placed in sand bags and dried at 60˚C for one day

Date	Activity or Measurement Details
	to reach the grain threshing and storage moisture range (8.89 - 16.5% wb) (Simonyan et al., 2007) (Appendix A.2.4).
17/03/2018	A Rimik CP40II cone penetrometer with soil sampling kit were used to monitor soil strength, bulk density and water content after ripping (third time). The second time procedure was used in this process.
20/03/2018	Threshing, de-awning and cleaning of sorghum seeds was carried out with a (CSIRO AF) WINTERSTEIGER LD 350 laboratory thresher (Figure 3-20, C).
22/03/2018	Before sorghum yield calculation, yield moisture was corrected according to the standard moisture for commercialization of sorghum grain which is 13.5% (GTA, 2015). Nine random samples of threshed sorghum grains (100 - 150 g) representing the experiment treatments and their blocks (D1-1, D1-2, D1-3, D2-1, D2-2, D2-3, C-1, C-2 and C-3) were prepared, weighed and dried at 100˚C for 40 hours (D.L. Antille, personal communication, May 31, 2017).

Figure 3-21: Evanslea site: (A) Folded Tilco eight tines ripper on the road, (B) On the experiment field's soil, (C) During (D1= 0 - 0.3 m), and (D2 = 0 - 0.6 m)

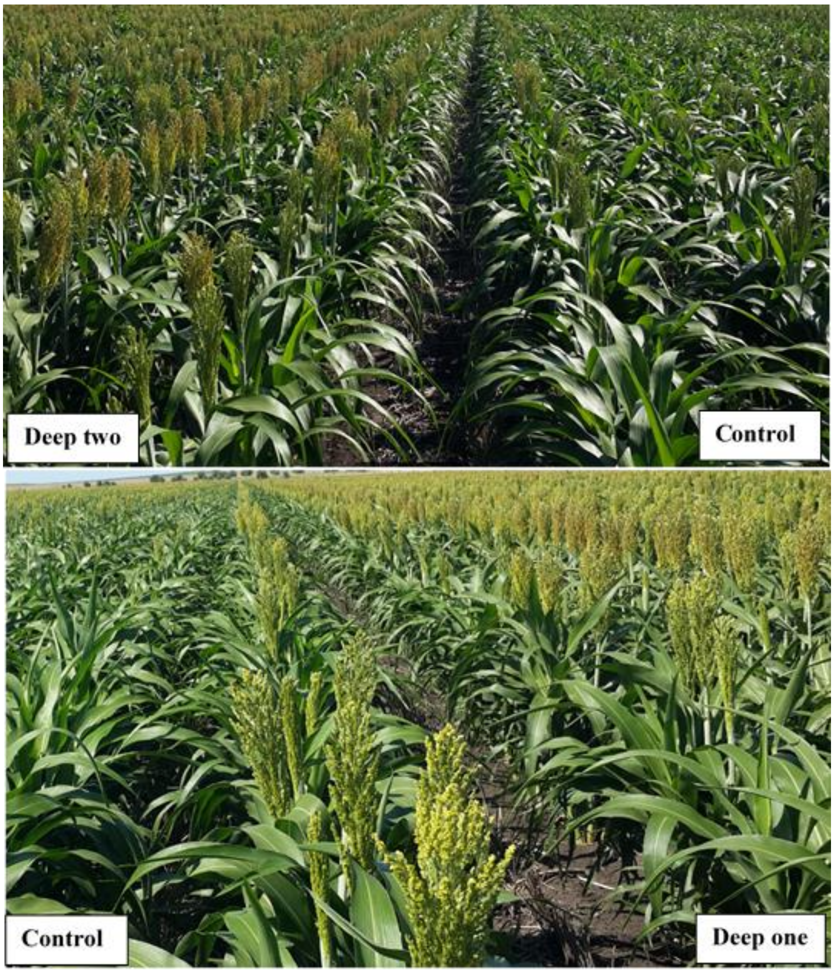

Figure 3-22: Evanslea site: Difference between C, D1, and D2 treatments during the sorghum growing season

3.1.8 The Studied parameters and calculation methods

The study parameters were divided into:

3.1.8.1 Soil parameters

- **Cone index**

Soil resistance against standard cone penetration was measured at both sites using a mounted Rimik® CP40II recording cone penetrometer to the constant drive device (Part A of Figure 3-12, and Appendix A.2.1) which consisted of an in-built data logger, an 0.8 m long shaft, a cone with a base area of 130 mm^2, a diameter of 12.83 mm, an apex angle of 30˚ (ASABE, 2014), and a 100 kg load cell (~ 7.5 M Pa). Insertions were made to a depth of 0.70 m with the resistance force automatically recorded at 25 mm (0.025 m). The values over the depth range 100 mm (four readings) were averaged and used as the mean penetration resistance (Marakoglu & Carman, 2009). Field measurements were uploaded for further analysis to a computer using the Rimik CP40II Retrieval 6.0 software (Rimik, 2004).

- **Bulk density**

Near the penetrometer bar spots, a stainless, and undisturbed core sampling tube was inserted to a depth of 0.8 m via hammering action of the Post Driver. After insertion, the tube was pulled with a foot lifter, and the soil was pushed out, very carefully and divided into 0.1 m increments (subsamples). The subsamples were placed into sealed foil-lined bags and processed in the laboratory. Brady and Buckman (1974) stated that bulk density is the mass of a unit volume of dry soil. At the laboratory, the soil samples were placed in a 105˚C oven for 72 hours. The bulk density was calculated according to the Brady and Buckman (1974) Equation 3-2.

$$\rho = W_d \ / \ V_s$$ ……………………………………………………..……. Equation 3-2

Where:

ρ = dry bulk density (g/cm^3),
W_d = dried soil weight (g), and
V_s = soil volume (cm^3).

The subsamples' volume was determined by multiplying their length (0.1 m) by the cross-sectional area of the soil core cutting tip.

- **Soil moisture content**

The moisture content was calculated from the same samples of bulk density. Moisture content of the soil was determined on a dry basis (*db*) Equation 3-3.

$$MC_{db} = ((W_i - W_d) / W_d) \times 100$$ …………………………………….. Equation 3-3

Where:

MC_{db} = moisture content, dry basis (%), and
W_i = initial weight of soil (g).

3.1.8.2 Crop parameters

- **Grain yield**

The yield was estimated based on the output from sampling a 1 m square unit per plot with three replications, and then calculated in kg/ha on the standard moisture for commercialization of cereals crop. The plot harvested (sorghum and wheat grain yield) area (m^2) was calculated by the length of the harvested row and the row spacing (Equation 3-4) (Chen et al., 2005). At both sites, grain was hand harvested from 3 m of the middle rows of each plot and threshed using a laboratory thresher located at Toowoomba CSIRO site. Subsamples were obtained from each harvested and threshed plot, weighed and dried for 40 hours at 100˚C (D.L. Antille, personal communication, May 31, 2017), and weighed again to correct the moisture content of each sample. Data were corrected according to cereal commercialization standard moisture which was 0.125 kg/kg moisture (12.5% moisture) for wheat and 0.135 kg/kg moisture (13.5% moisture) for sorghum. Equation 3-4 was used to measure the harvested area. Dry grains yield was expressed in kg/ha.

Harvested Area (m^2) = harvested row length (m) × row spacing (m) ….Equation 3-4

- **Dry biomass yield**

The crop biomass at both sites was estimated at harvesting time by hand-cutting whole plants in one meter of the middle rows of each plot to approximately 20 mm above ground level with three replications. This method was recommended for cereal sampling by Hudson (1939) cited in Millington, Misiewicz, Dickin, White, and Godwin (2016, p. 3). Equation (3-4) was used to measure the harvested (whole plant yield) area. Plants were then dried at 65 ˚C for three days and dry weights and recorded. Dry plant yield was expressed in kg/ha.

- **Harvest index**

Buah and Mwinkaara (2009) defined the HI as the ratio of grain yield to the aboveground biomass yield on an oven-dry weight basis. Thus, at the end of any crop season and during the manual harvesting, whole plants above the ground within one meter from each row and an average of four rows per plot were cut, dried at 60˚C for 24 hours to avoid grain breakage upon threshing, and then weighed. Then the heads were cut and taken to the Toowoomba CSIRO Agriculture & Food (CSIRO AF)

Organization Lab threshing machine for separation and weighing of the grains. The harvest index was then calculated using Equation 3-5.

HI_{db} = (dry grain yield (g) / dry biomass yield (g)) × 100 ………….. Equation 3-5

Where:

HI_{db} = harvest index, dry basis (%).

3.1.8.3 Machinery unit performance parameters

- **Draft force requirement**

The overall draft force was measured using a horizontal, calibrated, and bonded strain gauge (pull meter) which equals soil and crop resistance plus total implement motion resistance (ASABE, 2017) Standard EP496.3 (Equation 3-6). The pull meter was tied to one side of the drawbar at the driver (ahead) tractor and in other side to the front of the driven (neutral) tractor while the ripper penetrate soil to the required depth. Thereafter, the rear tractor rolling resistance was obtained while the tractor's three-point linkage was placed in its upper (no-load or float) position. The net draft force of ripper was then calculated through the difference between the overall draft force and the rolling resistance (Barger, Carleton, McKibben, & Bainer, 1952) (Equation 3-7). Draft measurements were scanned, recorded, and averaged at regular 2-second intervals and then stored via a digital datalogger which was located in the ahead (driver) tractor cab with full view.

$D = R_{S\&C} + MR$ ……………………………………………...… Equation 3-6

$D_{net} = D - MR$ ...……………………...………………………. Equation 3-7

Where:

D = implement overall draft force (N),
$R_{S\&C}$ = soil and crop resistance (N),
MR = total implement motion resistance (N), and
D_{net} = net implement draft force (N).

- **Power requirement**

According to Smith and Williford (1988) and Kichler (2008), power is a function of draft and ground speed. The net implement draft equation above is a prelude to estimating drawbar power requirement (kW) (ASABE, 2017) Standard EP496.3 (Equation 3-8).

$P_{dp} = (D_{net} \times V) / 3.6$ …………………………………...…………… Equation 3-8

Where:

P_{dp} = drawbar power required for the implement (kW),
V = velocity or travel speed (km/h), and
3.6 = constant.

3.1.8.4 Economic assessment

- **Cost of subsoiling**

In any agricultural project, machinery and equipment are the most important factors when considering cost (Edwards, 2015). In this study, several references, annual reports and guidelines were used to estimate the costs of deep ripping in accordance with Australian experiments conditions. Sources used include: Bainer et al. (1956), Culpin (1959), Schuler and Frank (1991), Pflueger (2005), Khairo and Davies (2009), Lazarus (2009), Edwards (2015), Hanna (2016) in addition to the annual machinery costs guides and guidelines (Appendix H.1). To estimate the total machine cost, the owning (fixed cost) and operating (variable cost) costs of the machine and/or implement should be estimated first.

Machine (tractor) costs

The accurate estimation of machine costs is necessary for some management decisions (Pflueger, 2005), and is an important factor for machine choice and use (Edwards, 2015; Taylor, Shrock, & Wertz, 1991). Costs arise from owning and operating the machine (power source) (Khairo & Davies, 2009). They can be divided into two categories, namely fixed costs and variable costs.

- ***Fixed costs (ownership cost)***

Occasionally, fixed costs are referred to as ownership costs since they are related to machinery ownership. They are paid annually regardless of whether the project machine was used for 0 h, 10 h or even 1,000 h (Pflueger, 2005). Ownership costs include the following:

- ***<u>Depreciation</u>***

Depreciation is a non-cash expense of machinery ownership resulting from the reduction in a machine's value over time because of wear, technological obsolescence and age. The actual depreciation cost is difficult to calculate but it can be estimated with several methods (Burnham & Hoskins, 1940). The straight-line method is the simplest and most common way to determine machinery depreciation cost. It gives a constant yearly charge for depreciation throughout the machine's lifespan. According to ASABE (2011), it can be calculated using Equation 3-9:

Annual depreciation cost = (new price - trade-in value) / expected life ... Equation 3-9

Trade-in value = new price × 0.1 ……………..…….……………………….…. Equation 3-10

Where:

Trade-in value = salvage value at the end of expected life (AUD), and
Expected life = number of years used (year). 10 to 15 years is used as an economic life for tractors. In most machinery costs guides, 12 years is considered the average of used period.

- ***<u>Interest (opportunity cost)</u>***

It is the lost interest income if the down payment had been invested in other productive enterprises or investments rather than buying the machinery. The real interest rate ranges between 5 to 10%. In this study, 7% was assumed to be an interest charge for the average investment of the machine. It can be calculated using Equation 3-11.

Average annual interest cost = average value × interest rate ……...…. Equation 3-11

Average value = (new price + trade in value) / 2 …………………….….. Equation 3-12

- ***<u>Insurance and housing cost</u>***

Both are fixed costs paid by most farmers to 1) insurance companies against accidents, natural disasters or fires and 2) build a suitable shelter to maintain the machine's value and performance. They can be lumped together as 1% of the average value. Insurance and housing (I&H) cost can be calculated using Equation 3-13.

I&H cost / year = average value × insurance and housing rate ……..…Equation 3-13

- ***Registration cost***

An incurred yearly registration cost to drive machinery on the roads.

Annual registration cost = registration cost for tractor ……………..… Equation 3-14

Where:

Tractor registration cost by the Roads and Traffic Authority (RTA) - QLD = 188.85 AUD/year.

- ***Variable costs (operating costs)***

Variable costs relate directly to the degree of machine utilisation. Its percentage varies as machine use varies. Thus, they are called sometimes as operating costs. The main variable costs for machinery are as follows.

- ***Repairs & maintenance cost***

Typically, the optimal life for each farm machine is measured in hours. Routine maintenance will therefore be performed after a certain number of hours while the engine is in a running state. These costs also include repair or replacement parts associated with normal use-wear or because of accidents. Machines repairs and maintenance vary for geographic region on account of topographic, soil type, climate, local costs, etc. They also differ from one farm to another in the same local area on account of farm management and maintenance programs and operator skill. Therefore, accurate estimates of these costs are not easily obtainable. However, the most practical method for estimating the annual cost of machinery repairs and maintenance (R&M) is as follows (Equation 3-15):

R&M cost / h = (R&M factor × new price) / yearly work ………Equation 3-15

Where:

R&M factor = 2% for engine-operated machinery in most machinery costs guides, and Yearly work = 1000 h which adopted by most machinery costs guide.

- ***Diesel fuel cost***

Fuel cost is dependent upon fuel consumption and its market price. Fuel consumption varies proportionally with engine power, loading, operating conditions and operator skill. Fuel costs can be calculated either by the hour or by the hectare. In recent years, global markets have witnessed dramatic fluctuations in monthly, seasonal and annual oil prices. Thus, for accurate estimation, fuel price must be adjusted according to current prices within tasked area. There are many methods to estimate fuel consumption, however we have used the actual figures for fuel consumption through the digital technology available in JD tractors. Then, diesel cost was calculated using Equation 3-16.

Diesel fuel cost / h = fuel consumption × fuel price ………….... Equation 3-16

Where:

Fuel consumption = number of consumed fuel (L/h), and

Fuel price = average monthly fuel value taken from QLD diesel tables of the Australian Institute of Petroleum (AIP) bulletins during experiments events (Appendix H.1).

- ***Lubrication cost***

Typically, replacing or adding of oils is performed during regular maintenance after limited hours of machine's operating. Since fuel consumption is entirely related to engine running, fuel costs are the best used indicator to calculate oil cost. Nebraska Tractor Test data and numerous surveys indicate that total lubrication costs on most farm power machinery average about 15% of fuel costs. Equation 3-17 was used to calculate this cost.

Lubrication cost / h = lubrication factor × fuel cost ……………… Equation 3-17

Where:

Lubrication factor = 15%

- ***Labour cost***

In machinery cost analysis, it is important to consider labour costs which vary in quantity depending on machine size and power. This rate will also vary depending upon the geographic location, availability individual's experience and skills. In the same way, labour costs depend on the type of labour used: owner-operators, hired operators, or permanent operators. Labour charge used to calculate machinery cost should never be less than a typical community labour rate (ASABE, 2011). As a rule, actual labour hours exceed machine operation hours because of time adjusting, hooking up, transporting, lubricating and servicing. Therefore, a 1.1 is used as labour adjustment factor to calculate total labour hours for machinery operation. The labour rate in this study was set at an average of AUD15/h based on a number of personal interviews with some workers and farmers in the Toowoomba region. Equation 3-18 was used to calculate labour cost.

Labour cost / h = labour wage rate / h × labour adjustment factor … Equation 3-18

Where:

Labour wage rate = AUD15/h, and
Labour adjustment factor = 1.1

Implement (ripper) costs

Estimating any tractor-attached equipment cost is very similar to the tractor cost calculation it is tied with, except that there are no fuel, lubrication, insurance, registration or labour costs involved. In addition, the farm equipment economic life for most farm machinery falls under Class 8 or Class 10 with yearly work of 300 h for a subsoiler. Detailed information to estimate the costs of owning and operating tractors and rippers costs during this study at the two sites, as well as contractor rates, can be found in Appendix B.1.1.

- **Benefits of subsoiling clayey soil**

The success of any adopted farm management plan is by the increasing economic benefits it achieves which, in turn, is achieved by increasing yield production, and this means increasing the farmer's satisfaction regarding profits (Chamen, 2015; CIMMYT, 1988). Economic benefit is divided into gross benefit (mostly called gross income or yield gains) and net benefit (mostly called gross margin). The gross income (GI) is the result of the treated area average yield (per weight unit) and the sales price (legal tender) for each weight unit. Accordingly, the following Equation 3-19 shows how to calculate GI for the Australian agricultural sector.

$GI = Y_{MO} \times P_C$ ………………………………………………………… Equation 3.19

Where:

GI = gross income (AUD/ha),
Y_{MO} = crop yield of management option (kg or tonnes / ha), and
P_C = crop price (AUD/kg or tonnes).

The gross margin (GM) can be defined as the gross farm income minus the total variable costs (TVC) incurred in achieving it. Equation 3.20 shows the net benefit or gross margin calculation.

$GM = GI - TVC$ …………………………………………………….. Equation 3-20

Where:

GM = gross margin (AUD/ha), and
TVC = total of variable costs (AUD/ha).

The Total Variable Costs (TVC) is the sum of field operations with seed and fertiliser cost. They should include the operations that have already been conducted and achieved the final production. Thus, the total costs have been calculated using the following equation.

$TVC = \sum$ fields operations, seeds and fertiliser costs ………………. Equation 3-21

Detailed information to measure GI, TVC, and GM during this study for season 2017 with two crops (sorghum + wheat) at the Ag plot site and for season 2018 with sorghum crop at Evanslea site can be found in Appendices B.2.1 and B.2.2.

At the Ag plot site, in addition to our recorded information throughout the trial period, a number sources were used to reach the final results (Appendix H.2.1). At the Evanslea site, Andrew was the main source for most of our inquiries, however other sources were used to confirm Andrew's information, or if an accurate answer could not be obtained (Appendix H.2.2).

3.1.9 Statistical analysis

Statistical analyses of the experimental data were conducted using the Statistical Package for Social Scientists (SPSS) software (Swan & Sandilands, 1995). Analysis of variance (ANOVA) was performed and the means compared using the least significant difference (LSD) at 5% probability level. Statistical analysis involved the

Duncan's Multiple Range Test (DMRT) (Duncan, 1955) to compare the specific differences between pairs of studied means data at the same level of probability. The results of the statistical analysis of the studied parameters' means obtained from the treatments and their interactions were presented in form of tables, columns or graphical curves for evaluation and discussion. Under various levels of deep ripping, the linear regression analyses were used to describe the relationships between the predicted draft force, crop grain and biomass derived from the G&O single tine and APSIM models. The empirical results were used to make a sound judgment regarding the validity of these models under these trial conditions. Analytical values were reported as the mean ± standard deviation (Std.).

3.1.10 Research difficulties and limitations

No experiment is free of some difficulties and limitations. These obstacles may even be critical when the experiment is conducted in an open system, especially agricultural experiments. Our project goal was to verify deep tillage feasibility in dense clay soils by studying its impact on the field power source (tractor), soil, crop, as well as the costs and profits. It represents a big challenge to the research team. We may be fortunate that the Ag plot's soil is classified as clay soil, however the challenge we experienced lay in the difficulty persuading farmers of the commercial clayey soil to proceed with this project as they believed that subsoiling could damage soil structure if not managed properly, and their concerns were considered legitimate. After disappointments, Mr. Andrew Ruhle finally expressed his agreement to harnessing a part of his commercial farm to conduct the research.

Targeting the crop from the first day of its emergence until it reaches the ripening and harvesting stage by huge numbers of birds represented by ducks and parrots in addition to rodents such as mice, rabbits and kangaroos, were among the obstacles that consumed a lot of time and efforts. After the university's administration realized the reality of the danger faced by the university's agricultural research crops by birds and rodents and the disappointment that confronted the aspirations of researchers, the university recently resorted to covering two fields with an area of 10,000 m^2 (one hectare) (T. Gillis, personal communication, July 23, 2020) for each plot and it considers an important step to increase the research productivity and its accuracy as well. We hope that the results of this research will be an encouraging factor for serious cooperation in future deep tillage projects with universities research, especially farms with high clay content soils.

3.2 Investigating the Godwin and O'Dogherty single tine model validity in two of Queensland high clay content soils

3.2.1 Godwin and O'Dogherty single tine model sensitivity

Before model validation, the sensitivity of the force prediction G&O single tine model was tested according to historical studies data: draft force requirement increase with increase tine depth (Ademosun et al., 2014; Harrison, 1988; Huijsmans et al., 1998; Rahman & Chen, 2001; Schaaf, Hann, & Lindwall, 1980; Zeng et al., 2017), speed (Bainer et al., 1956; Rahman & Chen, 2001), width (Araya, 1994a; Macmillan, 2002), rake angle (Hann et al., 1987a; Kapuinen, 1997; Marakoglu & Carman, 2009; Ndisya, 2016; Warner & Godwin, 1988), and soil softness (Negi et al., 1978; Stafford, 1981).

For soil parameters, three cases of clay soil density or bulk unit weight were assumed, high density 15 kN/m^3, average or moderate density 12.5 kN/m^3, and low density 10 kN/m^3 (constant) with cohesion value 16 kN/m^2 (constant) and 10° for internal fraction angle and interface friction angle value (constant). Soil adhesion was assumed to be zero. For tine parameters, six depths 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m, and 0.6 m and four forward speeds 0.56 m/s, 1.11 m/s, 1.67 m/s, and 2.22 m/s and six tine rake angles 20˚, 30˚, 40˚, 60˚, 70˚, and 90˚ were chosen. The tine width was chosen to be 0.05 m (constant). The results from running the model are presented graphically (Appendix C.1, C.2, C.3, and subdivides).

3.2.2 Sites description

The first investigation of G&O single tine model was at the Ag plot site (27˚36'35.54"S 51˚55'50.99"E) (Figure 3-23) on 02 December 2016. According to the key soil orders, the soil at this site is classified as a Red Ferrosol (Isbell, 2016). According to Gee and Bauder (1986), soil textural analyses for the bulked 0-0.8 m layer were 69.06% clay, 10% silt, and 20.94% sand.

At the Evanslea site (27˚30'42.98"S 151˚31'53.85"E), the G&O single tine model was investigated for the second time on 23 August 2017 (Figure 3.24). The soil classification at this site is Black Vertosol (Roberton, 2015). Through the Gee and

Bauder (1986) soil textural analyses procedure, the soil texture 0-800 mm layer were 64.79% clay, 23.44% silt, and 11.77% sand.

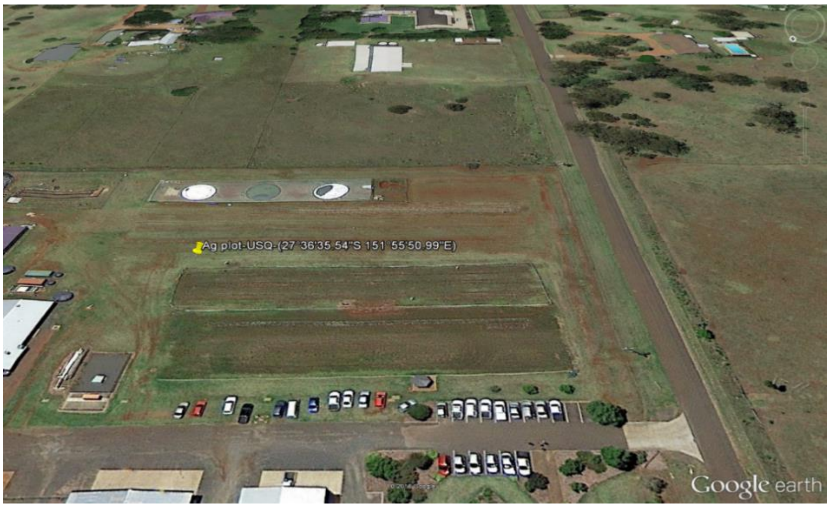

Figure 3-23: Ag plot site (Google Earth, 2016)

Figure 3-24: Evanslea site (Google Earth, 2017)

3.2.3 Materials used

At both sites, various tractors, devices, equipment and tools were used during G&O single tine model investigating. These are summarised in Table 3-6.

Table 3-6: Materials at used the Ag plot and Evanslea sites

Materials	Ag plot	Evanslea
Tractor/s	JD 6150 M and Belarus 920	JD 8400 and Ford 5000
Ripper	Barrow single tine	=
Pull meter	-	-
Data Logger	Rimik Digital Data-Node	=

Materials	Ag plot	Evanslea
Snatch strap	Ridge Ryder, 4WD – 15000 KG	=
Post driver (insertor)	Portable Christie's Engineering CHPD78	=
Lubricant spray	Boston 400 g	=
Core tubes	-	-
Extractor (lifter)	-	-
Scraper	Rhino Black 100 mm scraper	=
Table	Lifetime 6 ft bi-Fold blow mould trestle	=
Oven	Steridium, 800 L chamber capacities	=
Flags	Hand-made	=
Chicken bags	Chicken bags SM foil 213×165×58	=
Measuring tape	100 m and 8 m	=
Balance	HYPROP - max 2200 g	=
Stakes	Gardman 12 x 12 x 600 mm hardwood garden stake	=
Plastic bags	Plain LDPE 35 UM plain 330 x 230 mm	=
Hammer	Craftright 1.8 kg sledge hammer	=
Gloves	Rhino Goflex gloves	=
Storage container	The Award 50 litre plastic storage container with lid and 4 wheels	=
Stopwatch	Kenko digital quartz timer KK-5898	=
Dial gauge angle	Finder 0 to 90 degree indicator	=

Note: same (=), and locally made (-).

3.2.4 The measured draught force components (field)

In situ, the draught force of the Barrow single tine ripper was measured directly for each operational depth with motion resistance under selected theory velocity (2.7 km/h) and for a predetermined distance (100 m) with three replications. The following tractors, ripper and devices were used during this process.

3.2.4.1 The ahead and neutral tractors

At the Ag plot site, the JD 6150 M (engine: 150.0 hp [111.9 kW], PTO: 123.0 hp [91.7 kW], overall weight: 5929 kg was used as the ahead (driver) tractor (Figure 3-25 A) while the Belarus 920 ((engine: 100.0 hp [74.6 kW], PTO: 92.0 hp [68.6 kW], overall weight: 3900 kg)) was the neutral (driven) tractor (Figure 3-25 B). At the Evanslea site, the JD 8400 (engine: 250.0 hp [186.425 kW], PTO: 225 hp [167.8 kW], overall weight: 8486.2597 kg) was used as the ahead (driver) tractor (Figure 3-26 A) to pull the Ford 5000 (engine: 69.0 hp [51.5 kW], PTO: 60.37 hp [45.0 kW], overall weight: 2603.62 kg) which represented the neutral (driven) tractor (Figure 3-26 B).

Figure 3-25: Ag plot site: (A) JD 6150 M (ahead tractor), (B) Belarus 920 (neutral tractor), and (C) during model validity

Figure 3-26: Evanslea site: (A) JD 8400 (ahead tractor), (B) Ford 5000 (neutral tractor), and (C) during model validity

3.2.4.2 Single tine ripper

At both sites, a Barrow Subsoiler with a 0.095 m wide foot (tip), 0.205 m length foot, 35˚ foot rake angle, 0.04 m cross section of the straight shank, 0.151 m straight shank longitudinal section, and 0.7 m maximum subsoiler depth (Figure 3-27 A; B), was the single tine ripper connected to the neutral (driven) tractor via three-point linkage hitch. The depth levels were marked on the ripper shank. The studied depths were adjusted in advance of the field verification via the hydraulic system lock nut and the ripper shank' marked depths levels through a number of passes.

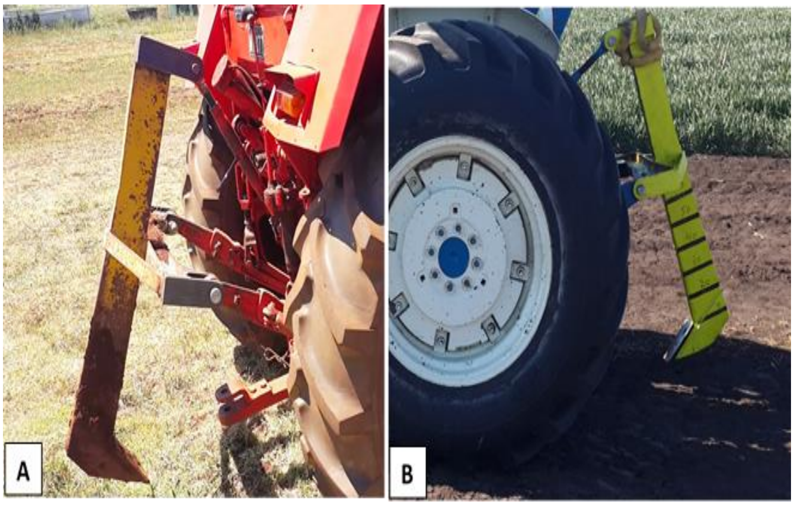

Figure 3-27: Barrow single tine ripper at (A) Ag plot site, (B) Evanslea site

3.2.4.3 Pullmeter apparatus and its accessories

A horizontal, calibrated and bonded strain gauge (pullmeter or dynamometer) with an overall draft load capacity of 30 tons (~ 300 kN) (Figure 3-28 A) was connected to one side of the drawbar of the ahead (driver) tractor and at the other side of the front of the neutral (driven) tractor to measure and average the draught force for 2 second intervals. The force was monitored, collected and saved by the data logger (Rimik digital Data-Node) (Figure 3-28 A) which was connected to the dynamometer and located inside the ahead (driver) tractor cab with full view.

3.2.5 The predicted draught force components (laboratory)

Laboratory, single tine Barrow ripper draught force was predicted by feeding the G&O single tine model with soil parameters: (bulk unit weight (γ), cohesion (c), internal friction angle (ϕ), surcharge (q), soil-metal friction angle (δ), and soil-metal adhesion (c_a)) and tine parameters: (depth (d), width (w), rake angle (α), and the velocity (v)). These parameters were identified using the following devices and tools.

3.2.5.1 ShearTrac-II direct shear apparatus

A strain-controlled direct shear test apparatus (ShearTrac-II), consisting of two metal rings with circular openings (McKyes, 1985) produced by Geocomp Corporation with up to 4.4 kN load capacity, was used to determine the cohesion, soil-metal adhesion, internal friction angle, and angle of soil-metal friction (Figure 3-29).

Figure 3-28: Pullmeter and Rimik digital data node, (B) Post driver and lifter, (C) Steel rings and steel block, (D) Dial gauge angle meter

Figure 3-29: Direct shear test (ShearTrac-II), Z1 Lab, USQ

3.2.5.2 Post driver and its accessories

A portable Christie's Engineering CHPD78 post driver equipped with a Honda GX35 4-stroke motor was used to push a hollow steel sampling tube to a 0.8 m depth (Figure 3-38 B). The soil-filled steel pipe was lifted by a foot lifter (Figure 3-28 B). The divided soil samples (0.1 m in length) and went through several field and laboratory steps to determine the bulk unit weight (kN/m^3) of soil depth.

3.2.5.3 Undisturbed soil kit

Steel rings with circular steel block (which fit the size of the direct shear device box) were used to collect undisturbed soil samples from the specific operation depths. Soil cohesion and the internal friction angle were determined by filling the device box with undisturbed soil (Figure 3-28 C) while the box filled with circular steel block (same ripper metal) and undisturbed soil (Figure 3-28 C) to determine the soil-metal adhesion and the angle of soil-metal friction (M. Kirby, personal communication, March 15, 2016).

3.2.5.4 Dial gauge angle with magnetic base

Within the operation depth, the tip rake angle was measured by dial gauge angle finder with magnetic base (Figure 3-28 D).

3.2.6 Field and laboratory application with parameter measurement methodology

At both sites, the investigation was conducted as follows: first, a 100 m field length was identified and flagged. Prior to the beginning flags, a length of ~ 5 m long was used as a practice distance to enable the neutral (driven) tractor with the ripper to reach the target ground speed and tillage depth (Figure 3-30). Before the trials, the Barrow subsoiler single tine ripper was connected to the neutral (driven) tractor via its three-point linkage hitch as shown in Figure 3-27 A and 3-27 B.

Over several passes, the ripper was raised and lowered hydraulically to calibrate the ripping depth level and then set the calibrated depth by a distance nut on the hydraulic cylinder. After that, the dynamometer was connected between the two tractors. The infinitely variable transmission (IVT) speed of the ahead (driver) tractor (JD) was set to a 2.7 km/h at full throttle. Tillage occurred at two depths: 1) 0 - 0.3 m, and 2) 0 - 0.6 m. The two tractors with pullmeter and single tine ripper moved through the 100 m distance at the respective treatment depths, three times. During the tests, treatments were repeated in the opposite direction to reduce the effect of soil topography. In this case, the dynamometer results represented both measured draught force and rolling resistance under two chosen depths (Equation 3-6) (Figure 3-31 A). Next, rolling resistance of the driven (neutral) tractor was obtained while the three-point linkage of the tractor was placed in its upper position, with three replications (Naderloo et al., 2009) (Figure 3-31 B). Thus, the net measured draft force for pulling the ripper under the specific depth was then calculated as the difference between the measured draft force and the rolling resistance value (Equation 3-7).

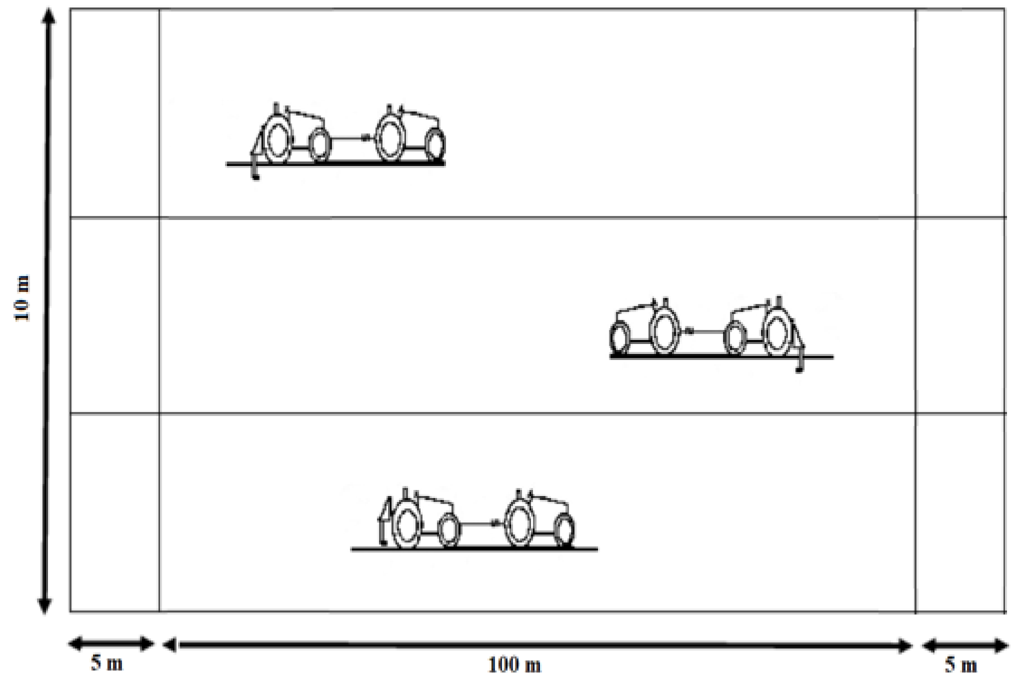

Figure 3-30: Trial design of investigation single tine model at Ag plot and Evanslea sites

In addition, the (real) time taken by the machinery unit (from the first flag to the second flag -100 m) was recorded for the treatment measurements to determine the practical speeds. At the end of each tillage run, and while the ripper was penetrating the soil, a shovel was used to dig the soil in front of the tip and the tip rake angle was measured by a dial gauge angle finder with magnetic base (figure 3-32 A, and 3-32 B). With a post driver using a hammering action, a stainless steel sampling tube was pushed to a depth of 0.8 m at 10 m intervals along the 100 m transect, to pull up soil samples. These samples were used to measure the soil bulk unit weight, dry bulk density and moisture content. The soil samples were carefully split into 0.1 m subsamples which resulted in 88 samples. The subsamples were emptied in sealed foil-lined bags and placed in the shade prior to further measurement.

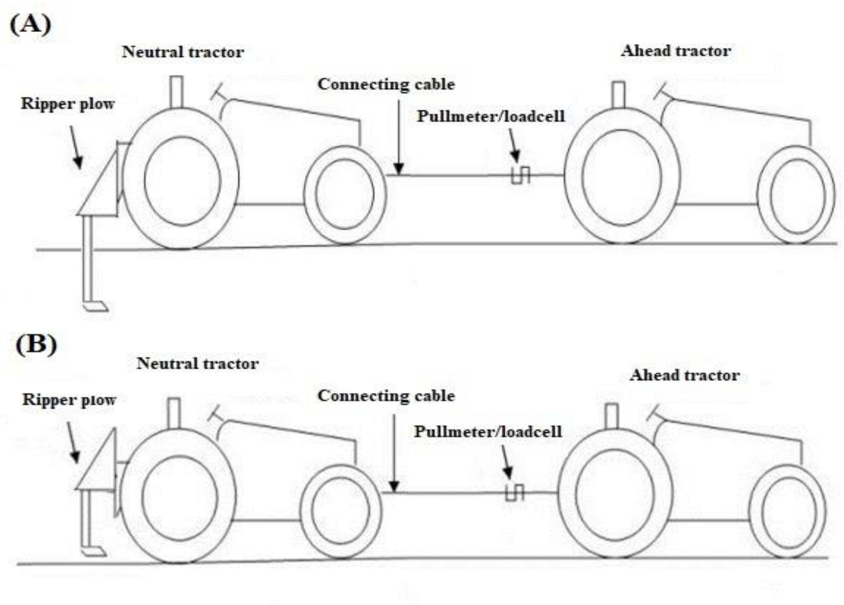

Figure 3-31: Field operation where a driven tractor is towed by a driver tractor with the dynamometer installed between them to measure: (A) Draught force of the single tine ripper (also containing rolling resistance), (B) rolling resistance

Figure 3-32: Measuring the tip rake angle via dial gauge with magnetic base while the ripper is penetrating the soil at each operation depth at: (A) Ag plot site, (B) Evanslea site

Subsamples were weighed as soon as possible after sampling to determine the field wet weight of each sample and bulk unit weight (kN/m^3). The bulk unit weight was calculated with the ratio of total wet or bulk weigh of subsamples to their volume (Lamb & Whitman, 1979) (Equation 3-22). The volume of subsamples was determined by multiplying their length (0.1 m) by the cross-sectional area of the soil core cutting tip. Then, subsamples were dried to constant weight at 105˚C for at least 72 h to determine the oven dry weight. Bulk density was then calculated by the ratio of oven-dry mass of the subsamples to their volume (Equation 3-2) while sample moisture content was determined by the difference of the wet and oven dry weights (Black, Evans, & Dinauer, 1965) (Equation 3-3).

Steel rings were used to provide undisturbed soil samples from the specific operational depths to fill the direct shear box device for measuring cohesion with the internal friction angle (Figure 3-33). The adhesion with soil-metal friction angle was measured by filling the bottom half of the direct shear device box with a circular steel block which represented the ripper metal, and the upper half was filled with undisturbed soil (Figure 3-34). Five normal forces (100.53 N, 157.19 N, 314.16 N, 471.24 N, and 628.32 N) were applied during the test and shear force applied was with a constant driving mechanism and recorded when the soil sheared for each normal force applied. The normal stress and the shear stress were given automatically through the facility of the device. The procedure was derived according to the ShearTrac-II instruction manual.

Figure 3-33: The undisturbed soil filling the direct shear box to measure cohesion and internal friction angle

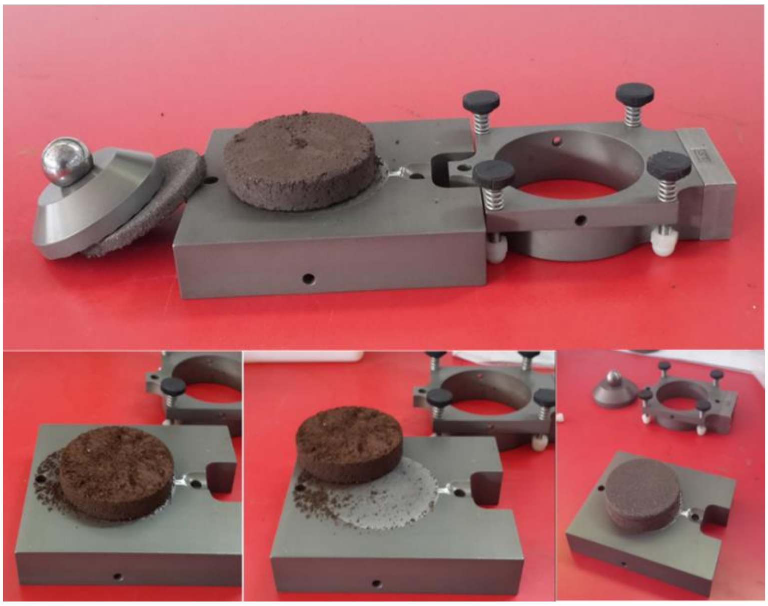

Figure 3-34: Undisturbed soil filling the upper half, while the bottom half was filled with a circular steel block to measure adhesion and soil-metal friction angle

3.2.7 Model validity

Godwin and O'Dogherty (2007) fed their model with tillage equipment geometry, working depth, soil physical properties data from Godwin and Spoor (1977), Godwin et al. (1984), Godwin, Seig, and Allott (1985) and Godwin and Wheeler (1996) experiments to predict the draft force and then compare it with measured draft force. They concluded that their model had the ability to predict draft force at an average error ranging between ± 20% of the measured forces. Thus, the decision of the model's validity was according to this standard.

3.2.8 The calculation of the model input parameters

For the G&O single tine model, the input parameters are divided into soil and tine parameters. The soil parameters were bulk unit weight, cohesion, internal friction angle, surcharge and angle of soil-metal friction. The tine parameters were depth, width, rake angle and the velocity.

3.2.8.1 Soil parameters calculation

- **Bulk unit weight**

Bulk unit weight is simply defined as the weight per unit area (Lamb & Whitman, 1979). It is calculated using the equation below:

$\gamma = W_i / V_s = (M \times g) / V_s = \rho \times g$ …………………….……... Equation 3-22

Where:

γ = bulk unit weight (kN/m^3)
W_i = initial (wet) soil weight (kilo newtons (kN),
M = initial (wet) soil mass (tonnes = 10^3 kg),
V_s = soil volume (m^3),
ρ = wet bulk density (tonnes / m^3 or g/cm^3), and
g = acceleration due to gravity (9.8 m/s^2).

- **Soil strength properties**

R.J. Godwin (personal communication, March 15, 2016) confirmed that tests on undisturbed soil samples from the range of operational depths gave appreciation of soil parameters. Thus, undisturbed soil samples of the operational depths were used to determine cohesion, adhesion, soil angle of the internal friction and soil-metal friction angle. Soil cohesion and its internal friction angle were determined using the direct shear test, based on the Mohr-Coulomb failure criterion, from a box filled with undisturbed soil. While adhesion and soil-metal friction angle were measured by filling one half of the direct shear box with a steel plate and the other half with undisturbed soil (M. Kirby, personal communication, March 15, 2016). Five normal force loads (100.53, 157.19, 314.16, 471.24 and 628.32 N) were applied during the test and shear force was applied with a constant driving mechanism and recorded when the soil sheared for each normal force applied. The normal stress and the shear stress were given automatically through the facility of the device. The procedure was derived according to the ShearTrac-II instruction manual.

- **Surcharge**

R.J. Godwin (personal communication, September 22, 2015) confirmed that surcharge equals zero when feeding the model.

3.2.8.2 Tine parameters calculation

- **Tine depth, width and rake angle**

R.J. Godwin (personal communication, September 22, 2015) confirmed use of the depth of tip, width of tip and rake angle of the single tine tip. The width of the *Barrow* single tine tip was 0.095 m and the rake angle of the tip was determined with a dial gauge angle finder with magnetic base while the ripper was penetrating the soil. The tine depth was calibrated on 0.3 m and 0.6 m for the operation D1 and D2, respectively.

- **Tine velocity**

The tine real velocity is the ratio of the specified distance to the real time.

$V = L / T$ ………………………………………………………….…….… Equation 3-23

Where:

V = velocity (travel speed) (m/s or km/h),
L = determined distance (100 m), and
T = real time (s or h).

3.3 Crop performance modelling work

Since its establishment 25 ago, the APSIM structure has evolved considerably to incorporate many models that simulate changes in agricultural landscapes, improved risk management in agricultural production, and with capability ranging from smallholders to large and remote farms. In this study, APSIM was employed to: 1) evaluate the impact of deep tillage systems on crop performance in two Queensland high clay content soils under long-term of climatic conditions (**Objective three**) and 2) from the long-term simulations, compare the predicted crop yields with the corresponding observed results from the experimental sorghum and wheat yields. Thus, providing the accuracy of APSIM's predictability which was the **fourth aim** of this study.

3.3.1 Model calibration

Under two intended levels of deep ripping (0-30 cm and 0-60 cm) with control (no tillage), the dryland wheat and sorghum crops were simulated at the Ag plot site, while the simulations involving dryland sorghum crop were conducted at the Evanslea - Toowoomba site. The soils used in the simulations were Red Ferrosol and Black Vertosol which were consistent with that used in the field studies at the Ag plot and Evanslea sites, respectively. The simulations were conducted on a continuous basis for 37 years (from 1980 to 2017) for the Ag plot crops and for 38 years (from 1980 to 2018) for the Evanslea crops. Historical climate data was obtained from the Queensland Government SILO database, http://www.longpaddock.qld. gov.au/silo (Jeffrey, Carter, Moodie, & Beswick, 2001).

The procedures used by Hussein (2018) and Antille, Huth, et al. (2016) were followed to assess the effect of deep tillage systems on crop physiological indices at the Ag plot and Evanslea, respectively. The yield of grain and dry biomass of two deep ripping and no ripping (control) systems to both types of clayey soil, were the guides used for the evaluation of APSIM model simulation. Winter wheat (*Spitfire*) and summer sorghum (*Elite Mr Buster*) were the two chosen crops for APSIM simulation in Red Ferrosol clayey soil at the Ag plot site during the 2017 season, while the model simulated summer sorghum (*Elite Mr Buster*) in Black Vertosol clayey soil at Evanslea - Toowoomba site on 2018 season.

3.3.2 Soil and water properties

At both sites, bulk density (ρ) soil samples under non-ripping (C), (D1 = 0 - 0.3 m) and (D2 = 0 - 0.6-m) system conditions were collected at a depth of 0.9 m to estimate the drained upper limit (DUL) and saturated water content (SAT). Saturated hydraulic conductivity (K_{SAT}) was measured at a depth of 0.6 m. For the Ag plot site, the ρ data for (0.9 - 1.2 m, 1.2 - 1.5 m, and 1.5 - 1.8 m) depth and K_{SAT} for (0.6 - 0.9 m, 0.9 - 1.2 m, 1.2 - 1.5 m, and 1.5 - 1.8 m) depth for (C) condition were derived from the non-CTF conditions of Red Ferrosol (same soil) data of Hussein (2018). From the available data on a comparable and under cropping Red Ferrosol soil of Dalgliesh and Foale (1998); Connolly et al. (2001), and on the same soil with cropping of Hussein (2018) under for CTF condition, the ρ data for 0.9 - 1.8 m depth and K_{SAT} for 0.6 - 1.8 m depth for D1 and D2 systems condition were derived and modified. For the Evanslea site, the data of ρ and K_{SAT} from 0.9 to 1.8 m and from 0.6 to 1.8 m depth respectively, for non-ripping (C) condition were derived from the APSIM-APSoil dataset, Dalgliesh and Foale (1998), Connolly et al. (2001), and Hochman et al. (2007). For D1 and D2 system conditions, the ρ and K_{SAT} data were derived and modified from similar Vertosol soil of Antille, Huth, et al. (2016), Dalgliesh and Foale (1998), and Hochman et al. (2001). Soil $pH_{1:5}$ (soil/water suspension) was 6.22 (Hussein, 2018) and 8 (Dalgliesh & Foale, 1998) for the Ag plot and Evanslea sites, respectively.

Saturated hydraulic conductivity (K_{SAT}) is the single most important hydraulic characteristic influencing soils water inflow (Zhang, Feng, Wang, Wang, & Li, 2012). For hydrological and crop models that use the water balance module, K_{SAT} is an important input parameter (Fodor, Sándor, Orfanus, Lichner, & Rajkai, 2011). For both C, D1, and D2 plot soil, K_{SAT} was measured using the constant head test procedure (Klute, 1965). The K_{SAT} values were determined by collecting the outflow leachate through the vertical soil column (core) in beakers placed under each column. Under constant head, the measurements of leachate volume and its required time with core dimensions were employed to measure Ksat via using the Hillel (2003) equation below:

$K_{SAT} = (V_l \times L) / (A \times H \times T)$ …………………………..……….…….. Equation 3-24

Where:

K_{SAT} = saturated hydraulic conductivity (mm/h or mm/day)
V_l = solution (liquid) volume (mm^3),
L = soil core length (mm),
A = soil core area (mm^2),
H = water head from base of core to top of solution (mm), and
T = time for V_l to flow through (h).

The Crop Lower Limit (CLL) value is the extent to which a crop can extract water from a particular soil type. CLL values have been estimated from the DUL and soil texture for both sites and for all soil depths (0 to 1.8 m) depending on developed rule of thumb pointers for heavy clay soils of (Dalgliesh & Foale, 1998; Hochman et al., 2001). The Lower limit of water content (LL) at the wilting point (-15 bar) was derived then from the available CLL values for both sites and for all depths using the Dalgliesh and Foale (1998) rules. Then, surface and subsurface air drying (AD) of both soils' depths (0 - 1.8 m) under three soil condition systems was also extracted from Dalgliesh's rules. Appendices D.1.1 and D.1.2 show the soil properties and input parameters used in the model.

DUL is defined as the amount of water (volumetric water %) that a particular soil holds after drainage has practically ceased (Gardner, Shaw, Smith, & Coughlan, 1984; Ratliff, Ritchie, & Cassel, 1983), so it is referred to as field capacity. It is water held against gravity and may only be removed by plants crops or weeds, or through evaporation. It was inferred from dry bulk density (ρ) (Equation 3-2) and gravimetric water content (Equation 3-3) for each depth interval using the Ratliff et al. (1983) procedure and Equation 3-25 (Burk & Dalgliesh, 2008; Dalgliesh & Foale, 1998).

$DUL (\%) = MC_{db} (\%) \times \rho (g/cm^3)$ …………………………………… Equation 3-25

As a consequence, soil water content at saturation (SAT) for each depth interval, is generally calculated from the total porosity (PO) which is determined from measured soil bulk density and an assumed particle density of 2.65 g/cm^3 (for each depth interval) using Equation 3-26. (Littleboy, Cogle, Smith, Yule, & Rao, 1996).

PO (%) = (1.0 - (ρ / 2.65)) × 100 ……………………......….. Equation 3-26

Saturation (SAT) is then calculated using Equation 3-27 (Dalgliesh & Foale, 1998; Gardner, Coughlan, & Silburn, 1988).

SAT (%) = (PO - e) × 100 ……………………………... Equation 3-27

Where:

e = assumed entrapped air % value for the particular textural class to be -3%, -5%, and -7% for clay, loams and sand soil, respectively.

After the availability and fed the above data, APSIM automatically calculates the Plant Available Water Capacity (PAWC). The PAWC is defined as the difference in volumetric water content between DUL (the highest measured field water content after drainage) and CLL (lowest measured water content when plants are very dry and leaves are either dead or dormant) (Ritchie, 1981, Carberry et al., 2009). Thus, PAWC is the maximum amount of stored soil water ready to be absorbed by plant roots (Hochman et al., 2001). The equations used to define PAWC and its associated variables can be viewed at the links on Appendix H.3.1.

3.3.2.1 Simulated crop data

The summer sorghum (*Elite Mr Buster*) was simulated to sowing every year between 15 October and 15 January which is in line with the farming practice where rainfall occurs (at least 0.025 m over a 7-day period). If rain does not fall or does not reach the specified amount for the start of sowing, the model was programmed to perform the sowing process at the end of January. At the Ag plot site, 81000 sorghum seeds were sown on one hectare with a row spacing of 0.9 m. At the Evanslea site, the hectare received 70000 of the same sorghum cultivar with a row spacing of 0.75m. Accordingly, the sowing density per square meter was 8.38 and 8.83 plants for the Ag plot and Evanslea sites, respectively. The urea-N fertiliser was applied 33 days after sorghum sowing at the Ag plot site which represented standard agronomic practice (Gerik et al., 2003).

The N was applied in rate of 140 kg/ha which was the optimum rate during a study conducted by Hussein et al. (2017) and Hussein (2018). At the Evanslea site, N applied as Anhydrous Ammonia with an actual rate of 100 kg/ha prior to sorghum planting, while Yara Flowphos 13Z was injected at a rate of 15L/h at sowing as a starter with N actual rate of 2 kg/ha.

The winter *Spitfire* wheat cultivar at the Ag plot site was simulated to sowing every year between 15 May and 15 July which is in line with the farming practice where rainfall occurs at least 0.02 m over a 5-day period. If the rain does not fall or does not reach the specified amount at sowing start, the model was forced to perform the sowing process at the end of July. 46 kg of wheat was sown on one hectare in the row spacing of 0.25 m in line with farming practice. Thus, the sowing density was 87 plants per square meter. The urea-N fertiliser was applied 37 days after wheat sowing at the beginning of tillering-Feekes 2.0 stage according to Miller (1999) recommendations. 110 kg of N was applied to each hectare, representing the optimum rate for the wheat season in the studies of Hussein et al. (2017) and Hussein (2018).

To simulate the effects of deep ripping depths on the yield of the crops' dry grain and biomass for long-term, the continued wheat and sorghum templates were chosen to start the APSIM simulation. The results of crop seeds and dry matter production of the study implementation year at both sites were also used to investigate model expectations validity after feeding with soil and climate conditions and the followed management policy.

The hand-harvested procedure was used to report the yield of the crops' dry grains and biomass in this study. Although the results of this procedure are often overestimated for commercial farm production due to lower harvesting loss, its results are accepted by the Australia grains industry when reporting commercial yields (Carberry et al., 2009). Most of the measured results were, therefore, higher than those predicted by APSIM, but they were within the model's validity limits. For sorghum, the simulated grain and dry biomass yields of the C, D1 and D2 tillage systems at the Ag plot site were lower than the corresponding measured data by 3.8%, 2.1% and 1.4% for grain and by 23.3%, 4.8% and 5.9% for biomass, respectively. At the Evanslea site, the measured sorghum grain and dry biomass production of C, D1 and D2 treatments were higher than the corresponding simulated data by 9.4%, 12.0%, and 10.4% for grain and 9.0%, 13.0%, and 12.7% for dry biomass, respectively. For wheat at the Ag plot site, the simulated grain yield for C, D1 and D2 systems were lower than the corresponding measured grain yield by 4.4%, 6.7% and 3.2% respectively, while for biomass, the same scenario was repeated with C and D1 where the simulations were lower than the corresponding measured data by 4.3% and 6.4%, respectively. The D2 treatment was higher than measured biomass by 2%. These differences are considered reasonable and support the validity of APSIM's prediction within the conditions of this study.

3.3.3 Validation judgment

The accuracy of any model can be achieved when its predicted outcomes are aligned with the study context and then can be judged as valid (Rykiel, 1996). Hearn (1994) concluded that the OZCOT model (one of APSIM’s original references) had predictability and its simulated values were in agreed with actual values of around 70% or more, so they were considered reasonable and good. Furthermore, Connolly et al. (2001) indicated that the accuracy of APSIM's prediction could be verified during the comparison between the measured and predicted data, when the variability in the predicted crop characteristics about the line y = x is consistent (R^2 close to one) and the general standard deviation is <100 for all variables tested, denoting that the model is accurate over the range of experimental data. Although APSIM's predicted grain yield value was over by up to 20% than the observed field data with the regression R^2 value of 0.65, it has been judged as valid at the conclusion of Peake, Robertson, et al. (2008). Therefore, the above criteria were adopted when evaluating the APSIM' predictability during this study.

3.3.4 Climate

For both experimental sites, simulations were conducted between 1980 and 2018 using SILO climate files (Jeffrey et al., 2001). Figures 3-45 and 3-46 show the long-term (38 year) rainfall and temperature for the two study areas. The Darling Downs, Queensland, Australia climate is characterised by moderate and semi-humid, with arid, cool winters and wet, warm to hot summers (Brennan et al., 2003; Cogle et al., 2011). During the simulated period, the average of annual rainfall was 835 and 584 mm at Ag plot (27˚36'36.25"S 151˚55'49.54"E) and Evanslea (27˚31'25.44"S, 151˚31'31.26"E) sites, respectively. The bulk of rainfall amount is concentrated during the summer months, which is characteristic of the Queensland climate (Perry, 1992). Over the studied period (1980-2018) and from climate files, 42% (351 mm) and 40% (233 mm) of the average annual rainfall were occurred during summer months (December, January and February) at Ag plot and Evanslea - Darling Down sites, respectively.

At the Ag plot site, the annual maximum temperature from 1980 to 2018 ranged between 16.6 ˚C in July and 28.2 ˚C in January, with an average of 23 ˚C. The annual minimum temperature ranged between 4.5 ºC in July and 17.0 ºC in January, with an average of 11.2 ˚C. At the Evanslea site, the average of annual maximum temperature for the same duration was 26.1 ˚C, ranging from 19.2 ˚C in July to 31.8 ˚C in January. For the same period, the yearly mean of recorded minimum temperatures was 11.6 ˚C (range: 18.4 ˚C in January to 3.7 ˚C in July).

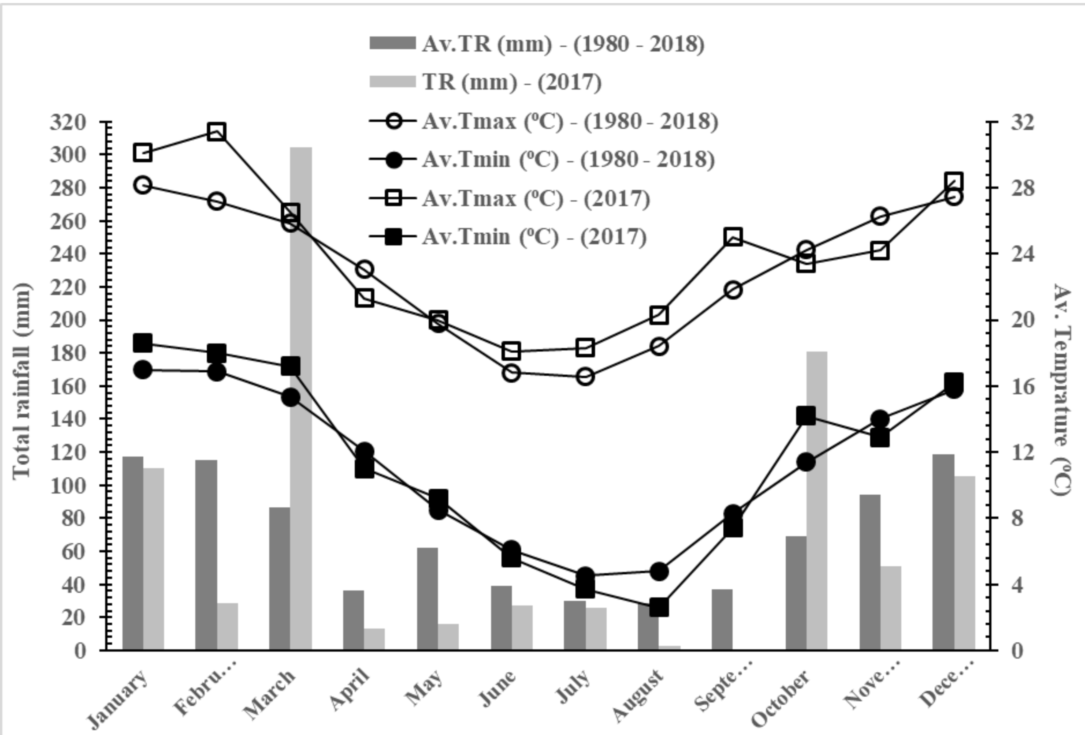

Figure 3-35: Shows 1) Monthly average of total rainfall (Av.TR), maximum temperature (Av. Tmax) and minimum temperature (Av. Tmin) for long-term (1980 - 2018), 2). Monthly average of total rainfall (TR), the monthly average of maximum temperature (Av. Tmax) and minimum temperature (Av. Tmin) for experiment year (2017) at Ag plot site (27˚36'36.25"S 151°55'49.54"E)

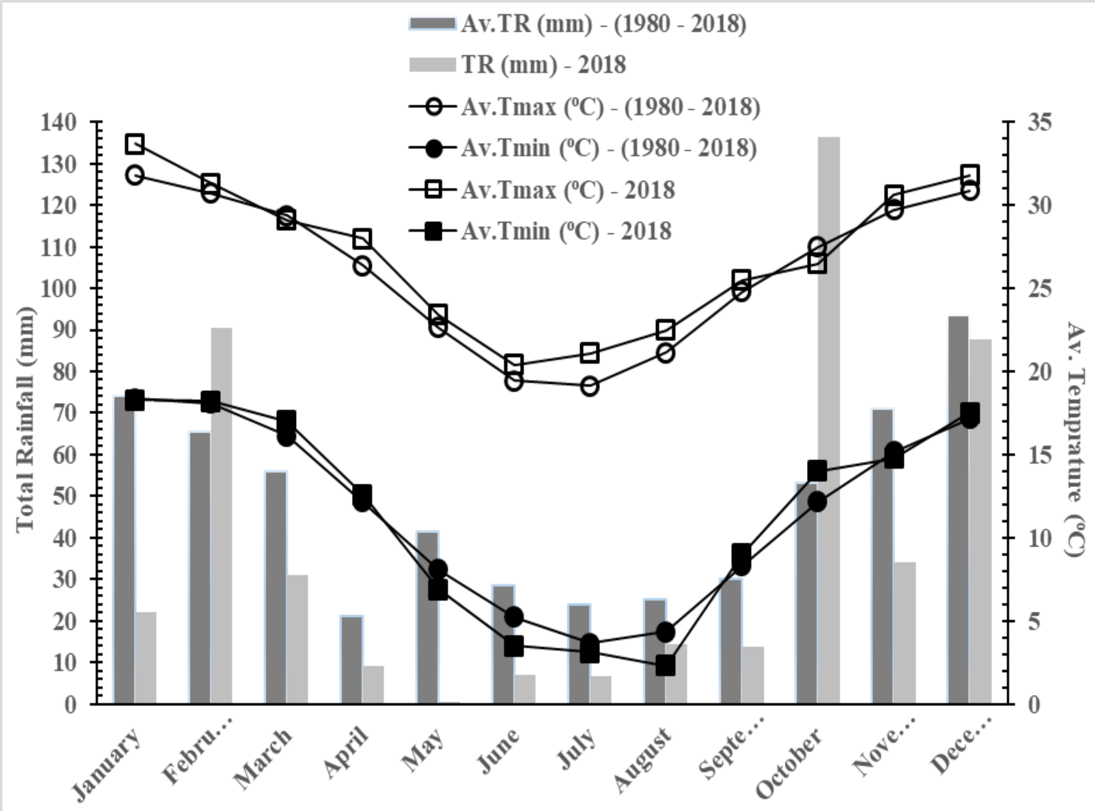

Figure 3-36: Shows 1) Monthly average of total rainfall (Av.TR), maximum temperature (Av. Tmax) and minimum temperature (Av. Tmin) for long-term (1980 - 2018), 2) Monthly of total rainfall (TR), the monthly average of maximum temperature (Av. Tmax) and minimum temperature (Av. Tmin), for experiment year (2018) at Evanslea site (27°31’25.44”S,151°31’31.26”E)

4. RESULTS AND DISCUSSION

4.1 Evaluation of deep tillage impact on soils, crops and benefits at two Queensland farms with high clay content soils

This section presents soil properties, plant yield, and the total and net benefits after deep tillage, and the indicators of machinery performance and costs during deep tillage at the Ag plot and Evanslea sites. The impact of fertiliser rates application after ripping systems practice on plant yield and total and net benefits, at the Ag plot site are also discussed.

4.1.1 Soil parameters

4.1.1.1 Dry bulk density

- **Ag plot site**

On this site, soil bulk density samples were taken over four times: before ripping on 20/11/2016, after ripping and during the sorghum season on 25/02/2017, after ripping and during the wheat season on 21/08/2017, and finally after ripping and about three months after wheat harvesting on 01/03/2018. It is noteworthy that deep ripping was performed a day after first sampling on 21/11/2016. Farming at this site was under the RTF system. Ripping was performed a day after first sampling on 21/11/2016. Farming at this site was under the RTF system.

In field experiments, the discussion of the tillage effect on soil properties should be within the tilled depth boundary (Unger & Fulton, 1990). However, the study went beyond the second depth boundary (60 cm) and discussed the ripping impact to 80 cm in depth.

Table 4-1 shows the average dry bulk density of the Red Ferrosol soil (Isbell, 2016) (along of 0-80 cm) for four dates and their interactions under (D1= 0-30 cm), (D2= 0-60 cm) and (C= control). It shows that, after three (on 25/02/2017), nine (on 21/08/2017) and fifteen (on 01/03/2018) months of the deep tillage application on 20/11/2016, the 0-30 cm ripping system significantly reduced soil bulk density from 1.40 g/cm^3 to 1.34 g/cm^3 (-4%) to 1.33 g/cm^3 (-5%) and then to 1.36 g/cm^3 (-3%), respectively. The 0-60 cm ripping system significantly reduced soil bulk density from

1.40 g/cm^3 to 1.31 g/cm^3 (-7%) to 1.31 g/cm^3 (-7%) and then to 1.34 g/cm^3 (-5%), respectively. Within the same period, the average soil dry bulk density of the control plots showed an increase (though not significant) from 1.40 g/cm^3 to 1.41 g/cm^3 to 1.41 g/cm^3 and then significant to 1.43 g/cm^3 (+2%), respectively.

Table 4-1 also shows the effect of the three tillage systems on soil depths. From the average densities of the studied soil sections for the four dates, both D1 and D2 had a clearly reduced the dry bulk density value. However, the most significant effect was from the 0-60 cm ripping. In general, over the study period and along the study depth of 80 cm, it can be seen that the shift from zero ripping to (D1) to (D2) resulted in a significant decrease in soil dry density from 1.41 g/cm^3 to 1.36 g/cm^3 and then to 1.34 g/cm^3, respectively. Thus, the first deep ripping (0-30 cm) reduced the dry bulk density value by 4%, while the reduction rate was 5% when the second deep ripping (0-60 cm) was applied.

Table 4-1 also shows the three average soil densities over the four dates and along the study depth sections (0-80 cm). Figure 4-1 clearly shows the dry bulk density behaviour during the studied dates and depths sections. For zero ripping soil, compared to the initial soil bulk density, the first soil section (0-10 cm) bulk density decreased significantly during the second and third dates from 1.25 g/cm^3 to 1.21 g/cm^3 (-3%) and then to 1.20 g/cm^3 (-4%) respectively but it returned to rise significantly more than the initial reading to 1.32 g/cm^3 (+6%) at the last date. Regarding the rest of the soil sections, the average overall dry bulk density increased during the following studied dates, most of which were not significant. The average dry bulk density of the total studied soil depth sections during the studied serial dates increased from 1.40 g/cm^3 to 1.41 g/cm^3 to 1.411 g/cm^3 and then to 1.43 g/cm^3, respectively. The increase was not significant except at the last date where it was significant (+2%).

As for the soil under the first depth of ripping (0-30 cm), compared to the soil initial readings, bulk density decreased over the study period and the soil sections. The decline was significant within the range of the impact of tillage and lower depths. This ripping concluded to reduce the average bulk density of soil sections significantly during the four dates from 1.40 g/cm^3 to 1.34 g/cm^3 to 1.33 g/cm^3, then to 1.36 g/cm^3, with an average of 4%, 5% and 3% compared to the first date. Most of the studied soil

Table 4-1: Soil dry bulk density (g/cm^3) along the Ag plot site soil depth (0-80 cm) for four dates in the short-term and their overlapping under two deep tillage systems (D1=0-30 cm and D2= 0-60 cm) with control (C= no ripping or zero ripping) system

Date	Date × Deep Ripping (cm)			Av. Date
	C = no ripping	D1	D2	
Nov. 2016	1.40 a	1.40 a	1.40 a	1.40 a
Feb. 2017	1.41 a	1.34 b	1.31 c	1.35 b
Aug. 2017	1.41 a	1.33 b	1.31 b	1.35 b
March 2018	1.43 a	1.36 b	1.34 b	1.38 c
Av. Deep Ripping	1.41 a	1.36 b	1.34 c	Tot. 1.37

Soil Depth (cm)	Soil Depth (cm) × Av. Deep Ripping (cm)			Av. Soil Depth
	C = no ripping	D1	D2	
0-10	1.25 a	1.16 b	1.18 b	1.19 a
10-20	1.41 a	1.34 b	1.25 c	1.33 b
20-30	1.42 a	1.39 a	1.33 b	1.38 c
30-40	1.43 a	1.39 b	1.38 b	1.40 d
40-50	1.44 a	1.41 a	1.42 a	1.42 e
50-60	1.43 a	1.42 a	1.38 b	1.41 d,e
60-70	1.45 a	1.40 b	1.37 b	1.41 d,e
70-80	1.48 a	1.38 b	1.40 b	1.42 d,e
Av. Deep Ripping	1.41 a	1.36 b	1.34 c	Tot. 1.37

C-Soil Depth (cm)	C - Soil Depth (cm) × Date				Av. C - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	1.25 a	1.21 b	1.20 b	1.32 c	1.25 a
10-20	1.41 a	1.42 a	1.40 a	1.42 a	1.41 b
20-30	1.41 a	1.40 a	1.43 a	1.43 a	1.42 b,c
30-40	1.41 a	1.42 a,b	1.45 b	1.45 b	1.43 c,d
40-50	1.43 a	1.43 a	1.43 a	1.46 a	1.44 d,e
50-60	1.41 a	1.44 a	1.43 a	1.44 a	1.43 c,d
60-70	1.43 a	1.45 a,b	1.47 b	1.46 a,b	1.45 e
70-80	1.48 a	1.48 a	1.48 a	1.48 a	1.48 f
Av. Date	1.40 a	1.41 a	1.41 a	1.43 b	Tot. 1.41

D1-Soil Depth (cm)	D1 - Soil Depth (cm) × Date				Av. D1 - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	1.25 a	1.09 b	1.08 b	1.21 c	1.16 a
10-20	1.41 a	1.24 b	1.30 c	1.40 a	1.34 b
20-30	1.41 a	1.38 a	1.38 a	1.40 a	1.39 c,d
30-40	1.41 a	1.38 a	1.39 a	1.39 a	1.39 c,d
40-50	1.43 a	1.41 a,b	1.39 b	1.41 a,b	1.41 d,e
50-60	1.41 a	1.43 a	1.41 a	1.42 a	1.42 e
60-70	1.43 a	1.44 a	1.35 b	1.38 b	1.40 d
70-80	1.48 a	1.38 b	1.35 b	1.30 c	1.38 c
Av. Date	1.40 a	1.34 b	1.33 c	1.36 d	Tot. 1.36

D2-Soil Depth (cm)	D2 - Soil Depth (cm) × Date				Av. D2 - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	1.25 a	1.10 b	1.13 b	1.23 a	1.18 a
10-20	1.41 a	1.15 b	1.17 b	1.27 c	1.25 b
20-30	1.41 a	1.23 b	1.32 c	1.37 d	1.33 c
30-40	1.41 a	1.37 b	1.36 b	1.39 a,b	1.38 d,e
40-50	1.43 a	1.41 a	1.42 a	1.42 a	1.42 f
50-60	1.41 a	1.39 a,b	1.37 b	1.36 b	1.38 d,e
60-70	1.43 a	1.40 a	1.34 b	1.32 b	1.37 d
70-80	1.48 a	1.40 b	1.37 b,c	1.34 c	1.40 e
Av. Date	1.40 a	1.31 b	1.31 b	1.34 c	Tot. 1.34

Note: Variation in letters and their mismatch are evidence of the significant effect, while the similarity of letters indicates that the effect is not significant

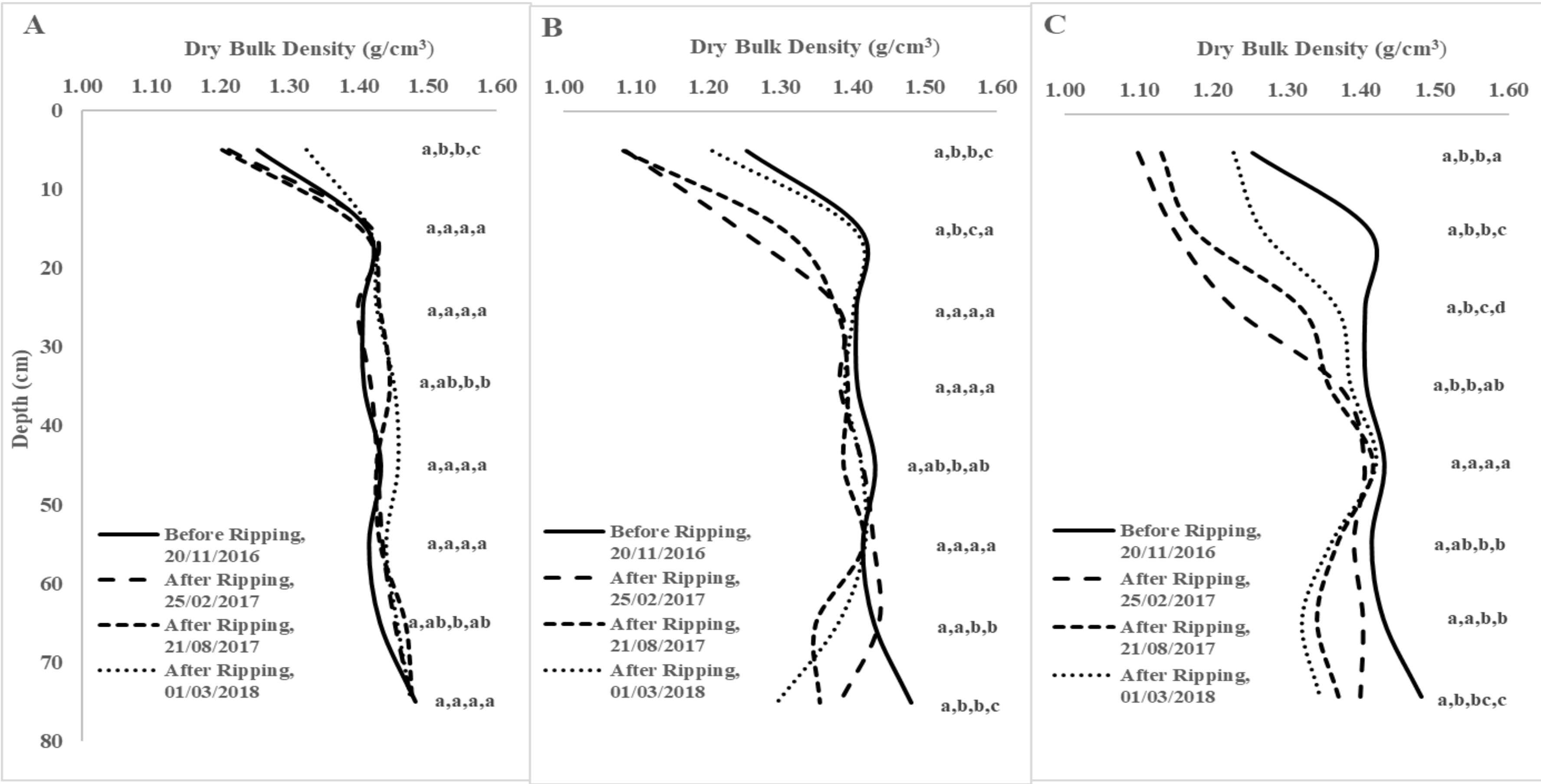

Figure 4-1: Soil dry bulk density (g/cm^3) for control (zero ripping) (A), D1 (B), and D2 (C) ripping .systems along soil depth of (0-80 cm) during the four dates at Ag plot - USQ - Toowoomba site. Note: variation in letters and their mismatch are evidence of the significant effect, while the similarity of letters indicates that the effect is not significant

sections experienced a significant decrease in dry densities when applying the 0-60 cm ripping. In these plots, the average dry bulk density decreased from 1.40 g/cm^3 to 1.31 g/cm^3 to 1.31 g/cm^3 and then to 1.34 g/cm^3, with a percentage decrease of 7% during the second and third dates and 5% during the fourth date compared to initial dry bulk density.

- **Evanslea site**

At this site, soil bulk density samples were taken three times: before ripping on 07/09/2017, after ripping on 04/11/2017, and finally after ripping and about thirteen days after sorghum harvesting on 17/03/2018. Ripping conducted after the completion of the soil sampling procedure on 07 /09/ 2017. The site was under the CTF system.

Table 4-2 shows the average dry bulk density for three dates along of 0-80 cm for Evanslea - Black Vertosol (Roberton, 2015) and their overlapping under deep ripping one (D1=0-30 cm), deep ripping two (D2=0-60 cm), and no or zero ripping (C= control) system.

From Table 4.2, it can be observed that during the first, second and third dates, the zero ripped soil suffered a significant increase in dry bulk density from 1.07 g/cm^3 to 1.09 g/cm^3 (+1%) and then to 1,09 g/cm^3 (+1%), respectively while the ripped soils experienced the opposite. The D1 significantly reduced the initial soil bulk density from 1.07 g/cm^3 to 1.06 g/cm^3 (-1%), then to 1.02 g/cm^3 (-5%) over the three dates, respectively. The same scenario was repeated with (D2), and within the same period, the dry bulk density was significantly reduced from 1.07 g/cm^3 to 1.01 g/cm^3 (-6%) and then to 0.98 g/cm^3 (-8%), respectively.

Table 4-2 also shows the average dry bulk density of the three soil sections (D1, D2 and C) for the study period. The table clearly shows that the soil section bulk densities decreased significantly for the applied deep ripping range, and below that range, the decrease was not significant. As a final result, the Control’s average soil bulk density for all sections and all periods decreased significantly from 1.08 g/cm^3 to 1.05 g/cm^3 (-3%) then to 1.02 g/cm^3 (-6%) when the level of ripping depth increased from 30 and then to 60 cm, respectively.

Table 4-2 : Soil dry bulk density (g/cm^3) at Evanslea site soil depth (0-80 cm) for three dates within in the short-term and their overlaps under two deep tillage systems (D1 = 0-30 cm and D2 = 0-60 cm) with control (C = no ripping or zero ripping) system

Date	Date × Deep Ripping			Av. Date
	C = no ripping	D1	D2	
Sep. 2017	1.07 a	1.07 a	1.07 a	1.074 a
Nov. 2017	1.09 a	1.06 b	1.01 b	1.053 b
March 2018	1.09 a	1.02 b	0.98 c	1.031 c
Av. Deep Ripping	1.08 a	1.05 b	1.02 c	Tot. 1.053
Soil Depth (cm)	Soil Depth (cm) × Av. Deep Ripping (cm)			Av. Soil Depth
	C = no ripping	D1	D2	
0-10	1.00 a	0.93 b	0.88 c	0.94 a
10-20	1.02a	0.97 b	0.93 c	0.97 b
20-30	1.05 a	1.00 b	0.99 b	1.01 c
30-40	1.10 a	1.03 b	1.01 b	1.05 d
40-50	1.08 a	1.06 a	1.02 b	1.05d
50-60	1.14 a	1.10 b	1.08 b	1.11 e
60-70	1.13 a	1.13 a	1.11 a	1.12 e
70-80	1.17 a	1.18 a	1.16 a	1.17 f
Av. Deep Ripping	1.08 a	1.05 b	1.02 c	Tot. 1.05
C-Soil Depth (cm)	C - Soil Depth (cm) × Date			Av. C - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	0.98 a	1.00 a	1.01 a	1.00 a
10-20	1.01 a	1.03 a	1.03 a	1.02 b
20-30	1.04 a,b	1.03 a	1.07 b	1.05, c
30-40	1.07 a	1.09 a	1.13 b	1.10 d
40-50	1.08 a	1.08 a	1.07 a	1.08 e
50-60	1.13 a,b	1.16 a	1.12 b	1.14 f
60-70	1.12 a	1.14 a	1.12 a	1.13 f
70-80	1.16 a,b	1.19 a	1.15 b	1.17 g
Av. Date	1.07 a	1.09 b	1.09 b	Tot. 1.08
D1-Soil Depth (cm)	D1 - Soil Depth (cm) × Date			Av. D1 - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	0.98 a	0.89 b	0.93 c	0.93 a
10-20	1.01 a	0.91 b	0.99 a	0.97 b
20-30	1.04 a	1.00 b	0.97 b	1.00 c
30-40	1.07 a	1.05 a	0.97 b	1.03 d
40-50	1.08 a	1.11 a	1.00 b	1.06 e
50-60	1.13 a	1.15 a	1.03 b	1.10 f
60-70	1.12 a	1.14 a	1.12 a	1.13 g
70-80	1.16 a	1.21 b	1.16 a	1.18 h
Av. Date	1.07 a	1.06 b	1.02 c	Tot. 1.05
D2-Soil Depth (cm)	D2 - Soil Depth (cm) × Date			Av. D2 - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	0.98 a	0.79 b	0.86 c	0.88 a
10-20	1.01 a	0.86 b	0.92 c	0.93 b
20-30	1.04 a	0.96 b	0.97 b	0.99 c
30-40	1.07 a	1.01 b	0.96 c	1.01 d
40-50	1.08 a	1.02 b	0.97 c	1.02 e
50-60	1.13 a	1.08 b	1.02 c	1.08 f
60-70	1.12 a	1.15 a	1.07 b	1.11 g
70-80	1.16 a	1.22 b	1.10 c	1.16 h
Av. Date	1.07 a	1.01 b	0.98 c	Tot. 1.02

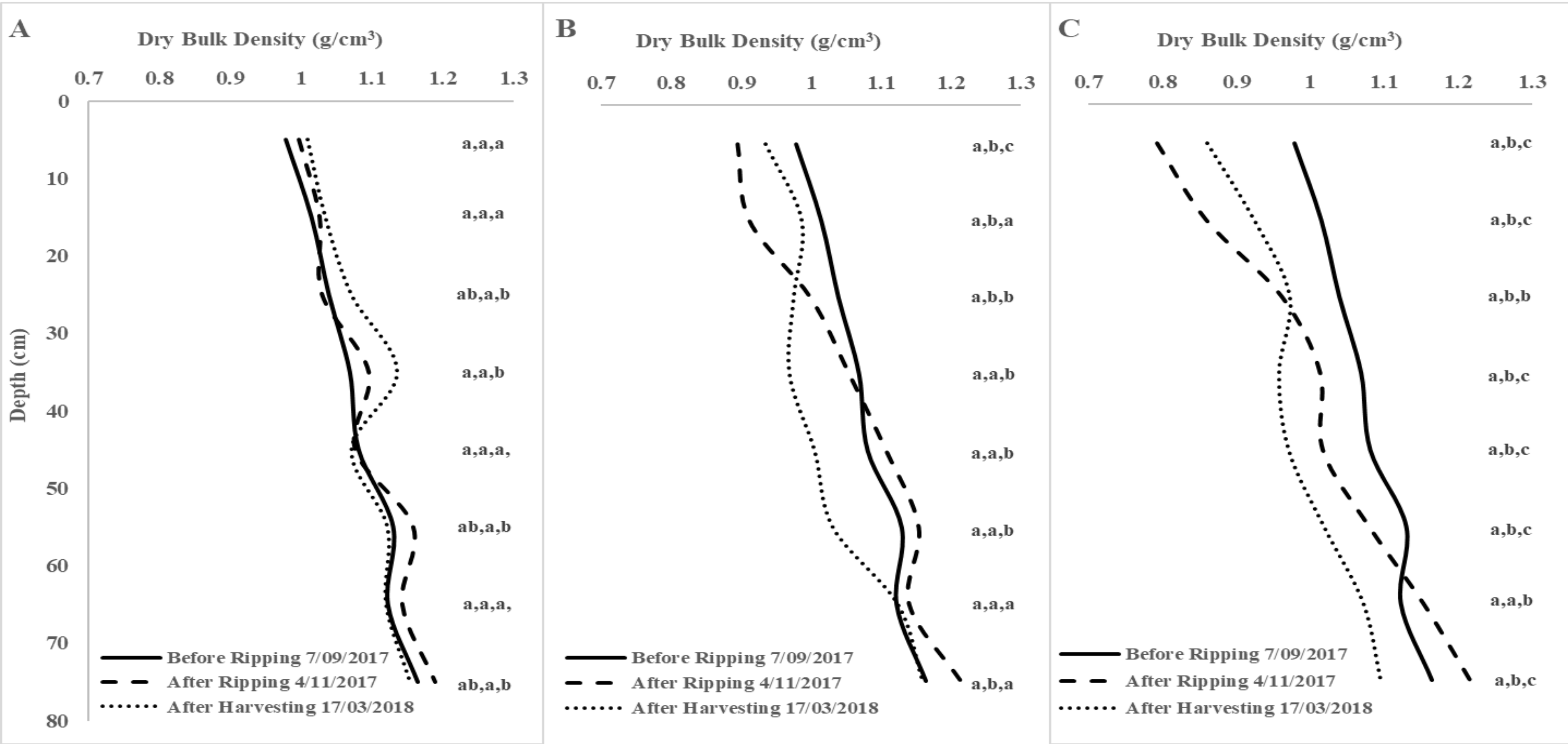

Figure 4-2: Soil dry bulk density (g/cm^3) for control (zero ripping) (A), D1 (B), and D2 (C) ripping systems along soil depth of (0-80 cm) during the three dates at the Evanslea site. Note: variation in letters and their mismatch are evidence of the significant effect, while the similarity of letters indicates that the effect is not significant

Table 4-2 shows each section's soil dry bulk density along 0-80 cm for the three dates. In addition, Figure 4-2 depicts each section's soil behaviour and dry bulk density along 0-80 cm on each date. The dry bulk density of the Control soil segments increased on the second date, but this was not significant. On the third date, the root zone experienced an increase in its density (though not significant). Below this region, the dry bulk density returned to be somewhat close to the initial values. In sum, the average of section bulk densities increased significantly from 1.07 g/cm^3 to 1.09 g/cm^3 and then 1.09 g/cm^3 on the three consecutive dates, respectively.

The dry bulk density of soil sections within the range of D1 (0-30 cm) had significantly decreased on the second date. Below the ripping range, the section bulk densities experienced an increase compared to the initial values (though not significant). On the third date, despite the root zone bulk density increased compared to the previous dates' values, the rest of the soil sections experienced a decrease in their bulk density to be close to the initial values and lower than the previous values. In general, Table 4-2 shows that the dry bulk density of this soil decreased significantly from 1.07 g/cm^3 to 1.06 g/cm^3, then to 1.02 g/cm^3 during the three dates, respectively.

Regarding the soil under D2, on the next date, most of its sections experienced a significant decrease in their dry bulk densities compared to the initial dry bulk density values. On the third date, the shallow depth bulk density values experienced a significant increase compared to the second date, while the following sections experienced a continued significant decrease in their bulk densities. In general, the average dry bulk density of these plots decreased significantly from 1.07 g/cm^3 to 1.01 g/cm^3 to 0.98 g/cm^3 on the three studied dates, respectively.

As presented above, for both sites, deep ripping significantly reduced the two soils' initial bulk density across the study period and the studied depth. Also, from the above tables and figures' results, it can be concluded that the average decrease in soil dry bulk density value increases as ripping depth increases. This may be because deep ripping increases soil looseness which increases the porosity and aeration of the soil layers, which may lead to an increase in soil volume and a decrease in its mass within the soil column, which in turn may reduce soil bulk density. In addition, ripping could reduce soil strength and increase the elongation and density of plant roots, which may also contribute to the reduction of soil bulk density. Increased tine/s ripper penetration depth may also increase the amount of soil affected by looseness, aeration and porosity. Thus, soil dry bulk density value could also be reduced.

At the Ag plot site, the reason for the significant decrease in dry bulk density of the first 10 cm of zero ripped soil during the second and third dates may be due to the use of a rotary hoe to prepare the sorghum and wheat seedbed before planting. As for the fourth date, the dry bulk density of this depth increased significantly due to crop and harvest service operations. The high average temperature (28.2˚C) and low rainfall (229.6 mm) during the summer season (December, January, February) (Figure 3-35) could be another reason for increased soil dry bulk density.

In contrast, D1 and D2 soil dry bulk density on the second date (after ripping) decreased. This may be due to the tillage effect. Also, soil section dry bulk density below ripping depth decreased. This may be attributed to the increased amount of water and air penetrating these layers, causing an increase in pore size leading to a decrease in soil section dry bulk density. On the third and fourth dates, ripped levels experienced an increase in dry bulk density. Crop service and harvest operations, high temperature and low rainfall are highly likely to be the reasons. At the same time, section dry bulk density below the ripping boundary decreased. This may be attributed to the good moisture, air pore size and soil stability.

At the Evanslea site which was under the CTF system, the Vertosol soil sections experienced a significant increase in dry bulk density on the second and third dates compared to the first date. The explanation for this may be the acute decrease in rainfall, 85.7 and 229.9 mm, along with an increase in the average temperature of 27.6 and 31.6˚C, during these two dates (Figure 3-36), respectively. Under these conditions, it is highly likely that the soil shrink (Connolly et al., 1997; Connolly et al., 2001), causing an increase in the soil mass within its volume unit, thus bulk density values will be increased. The frequency of passing of crop service equipment during the growing sorghum season, as well as harvesters at the end of the season, may also be a reason as it will generate a load on the soil, causing soil section dry bulk density values to increase.

The D1 and D2 plots of the Evanslea site were similar in section behavior regarding soil bulk density over the studied dates. On the second date, soil section bulk density in ripping depth decreased and this may be (as mentioned previously) due to increase soil looseness, pore size and soil aeration. However, the soil sections below ripping level experienced an increase in dry bulk density compared to the initial densities (though not significant). This can be attributed to several reasons including the pressure applied by the eight ripper tines' feet during tillage which may compact these soil sections and increase their bulk densities. Also, high air temperature, soil permeability, porosity and decreased rainfall may cause shrinkage in these soil sections due to evaporation of stored water, thus increasing bulk density.

On the third date, for both soils, the root zone (0-25) bulk density increased significantly, while the lower soil sections experienced a significant decrease in their bulk densities. High temperatures and lack of vegetation after harvest may have led to an increase in the upper soil sections' water evaporation, which in turn led to increased soil cohesion and shrinkage, thus increasing the bulk density. The lower soil sections, however, are highly likely to have experienced stability in their structure and stored water content which could lead to improved porosity and, consequently, a decrease their bulk density.

From the above, it becomes clear that a combination of deep ripping and CTF system over time, not only reduced soil bulk density in the tillage range, it increased the reduction of soil section bulk density below the ripping level.

4.1.1.2 Soil moisture content

- **Ag plot site**

Table 4-3 shows the average moisture content for the four dates along 0-80 cm for the Ag plot Red Ferrosol soil and their overlaps under (D1=0-30 cm), (D2= 0-60 cm), (C= control) system. The table shows that the average moisture content of the Control plots on the first date, 26.86%, decreased to 26.50% and increased to 27.05% and then to 27.27%, on the second, third and fourth dates (though not significant), respectively. Also, the average moisture content of D1 plots on the first date, 26.86%, significantly decreased to 25.50% (-5%) and then increased significantly to 28.05% (+4%) and then to 28.13% (+5%), respectively.

The D2 moisture story was the same as the D1 story, but with different values. The table shows that the average moisture content of D2 plots on the first date, 26.86%, significantly decreased to 25.31% (-6%) and then increased significantly to 28.51% (+6%) and then to 28.41 % (+6%), respectively.

The table also shows the effect of D1, D2 and C treatments on soil section moisture content over the study period. The wetness approach for the three studied soils was similar. They increased with increasing depth and decreased when heading towards the soil surface. However, the differences between moisture values were significant for the surface sections in the root zone in general and became not significant for sections below this zone. In addition, the table shows that section moisture content increased with increasing ripping depth.

Table 4-3 shows that the average moisture content across the studied period and soil depth increased from 26.92% to 27.14% and then to 27.28% with increasing tillage from zero to 30 cm, and then to 60 cm. However, the differences were not significant.

The section moisture content values for each studied soil on the four dates are shown in detail in this table up to 80 cm as well. Figure 4-3 gives clarity to the moisture behaviour as it turns these values into continuous and dashed lines, representing the dates for each soil separately. With regard to the zero ripped soil, there were no significant differences between the sections' moisture mean values over the four dates except for the 0-10 and 10-20 cm sections which experienced a significant increase on the third and fourth dates compared to the first and second dates. In sum, the initial moisture column of this soil (26.86%) decreased to 26.50% on the second date, then rose on the third and fourth dates to 27.05% and 27.27%, respectively. The differences were not significant except for the second and fourth dates (+3%).

On the second date (after ripping), for both D1 and D2 soils, all soil sections have experienced a decrease in their moisture content values compared to the first date. This decrease was significant across the level of ripping depth. On the third and fourth dates, all soil sections experienced an increase in their moisture content. This increase was also significant within the subsoiling boundaries compared to the first date. In general, the average moisture content of all D1 soil sections on the first date (26.86%) decreased significantly to 25.50% (-5%) on the second date, and after that increased significantly to 28.05% (+4%) and 28.13% (+5%) on the third and fourth dates, respectively. Likewise, the mean moisture content of all D2 soil sections during the first date (26.86%) decreased significantly to 25.31% (-5%) during the next date and

Table 4-3: Soil moisture content (%) at the Ag plot site soil depth (0-80 cm) for four dates in the short-term and their overlapping under two deep tillage systems (D1 = 0-30 cm and D2 = 0-60 cm) with control (C = no ripping) system

Date	Date × Deep Ripping (cm)			Av. Date
	C = no ripping	D1	D2	
Nov. 2016	26.86 a	26.86 a	26.86 a	26.86 a
Feb. 2017	26.50 a	25.50 a	25.31 a	25.77 b
Aug. 2017	27.05 a	28.05 a	28.51 a	27.87 c
March 2018	27.27 a	28.13 a	28.41 a	27.94 c
Av. Deep Ripping	26.92 a	27.14 a	27.28 a	Tot. 27.11

Soil Depth (cm)	Soil Depth (cm) × Av. Deep Ripping (cm)			Av. Soil Depth
	C = no ripping	D1	D2	
0-10	23.02 a	23.15 a	23.23 a	23.13 a
10-20	25.27 a	25.57 a	25.22 a	25.35 b
20-30	26.76 a	26.38 a	26.70 a	26.61 c
30-40	26.94 a	27.49 a	27.32 a	27.25 c,d
40-50	27.31 a	27.60 a	27.79 a	27.57 d
50-60	27.85 a	28.01 a	28.58 a	28.15 d
60-70	28.84 a	29.19 a	29.57 a	29.20 e
70-80	29.39 a	29.69 a	29.80 a	29.63 e
Av. Deep Ripping	26.92 a	27.14 a	27.28 a	Tot. 27.11

C-Soil Depth (cm)	C - Soil Depth (cm) × Date				Av. C - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	22.35 a,b	20.74 a	23.52 b	25.45 c	23.02 a
10-20	25.06 a,b	24.36 a	25.41 a,b	26.24 b	25.27 b
20-30	26.59 a	26.29 a	26.87 a	27.29 a	26.76 c
30-40	27.25 a	26.68 a	27.00 a	26.83 a	26.94 c
40-50	27.55 a	27.28 a	27.33 a	27.07 a	27.31 c,d
50-60	28.26 a	28.12 a	27.70 a	27.31 a	27.85 d
60-70	28.89 a	28.92 a	28.87 a	28.67 a	28.84 e
70-80	28.92 a	29.60 a	29.72 a	29.31 a	29.39 e
Av. Date	26.86 a,b	26.50 a	27.05 a,b	27.27 b	Tot. 26.92

D1-Soil Depth (cm)	D1 - Soil Depth (cm) × Date				Av. D1 - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	22.35 a	19.94 b	24.51 c	25.81 c	23.153 a
10-20	25.06 a	22.69 b	27.29 c	27.22 c	25.565 b
20-30	26.59 a	23.80 b	27.49 a	27.65 a	26.382 c
30-40	27.25 a,b	26.72 a	27.58 a,b	28.40 b	27.487 d
40-50	27.55 a,b	26.61 a	28.29 b	27.94 a,b	27.598 d
50-60	28.26 a,b	27.02 a	28.88 b	27.89 a,b	28.013 d
60-70	28.89 a	28.45 a	29.91 a	29.50 a	29.188 e
70-80	28.92 a,b	28.73 a	30.48 b,c	30.64 c	29.693 e
Av. Date	26.86 a	25.50 b	28.05 c	28.13 c	Tot. 27.135

D2-Soil Depth (cm)	D2 - Soil Depth (cm) × Date				Av. D2 - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	22.35 a	19.55 b	24.97 c	26.04 c	23.23 a
10-20	25.06 a	22.15 b	27.11 c	26.54 a,c	25.22 b
20-30	26.59 a	24.36 b	28.19 a	27.66 a	26.70 c
30-40	27.25 a	25.37 b	28.79 a	27.85 a	27.32 c,d
40-50	27.55 a,b	26.21 a	28.58 b	28.82 b	27.79 d,e
50-60	28.26 a,b	27.50 a	29.51 b	29.05 a,b	28.58 e
60-70	28.89 a,b	28.52 a	30.32 b,c	30.56 c	29.57 f
70-80	28.92 a	28.85 a	30.64 b	30.78 b	29.80 f
Av. Date	26.86 a	25.31 b	28.51 c	28.41 c	Tot. 27.28

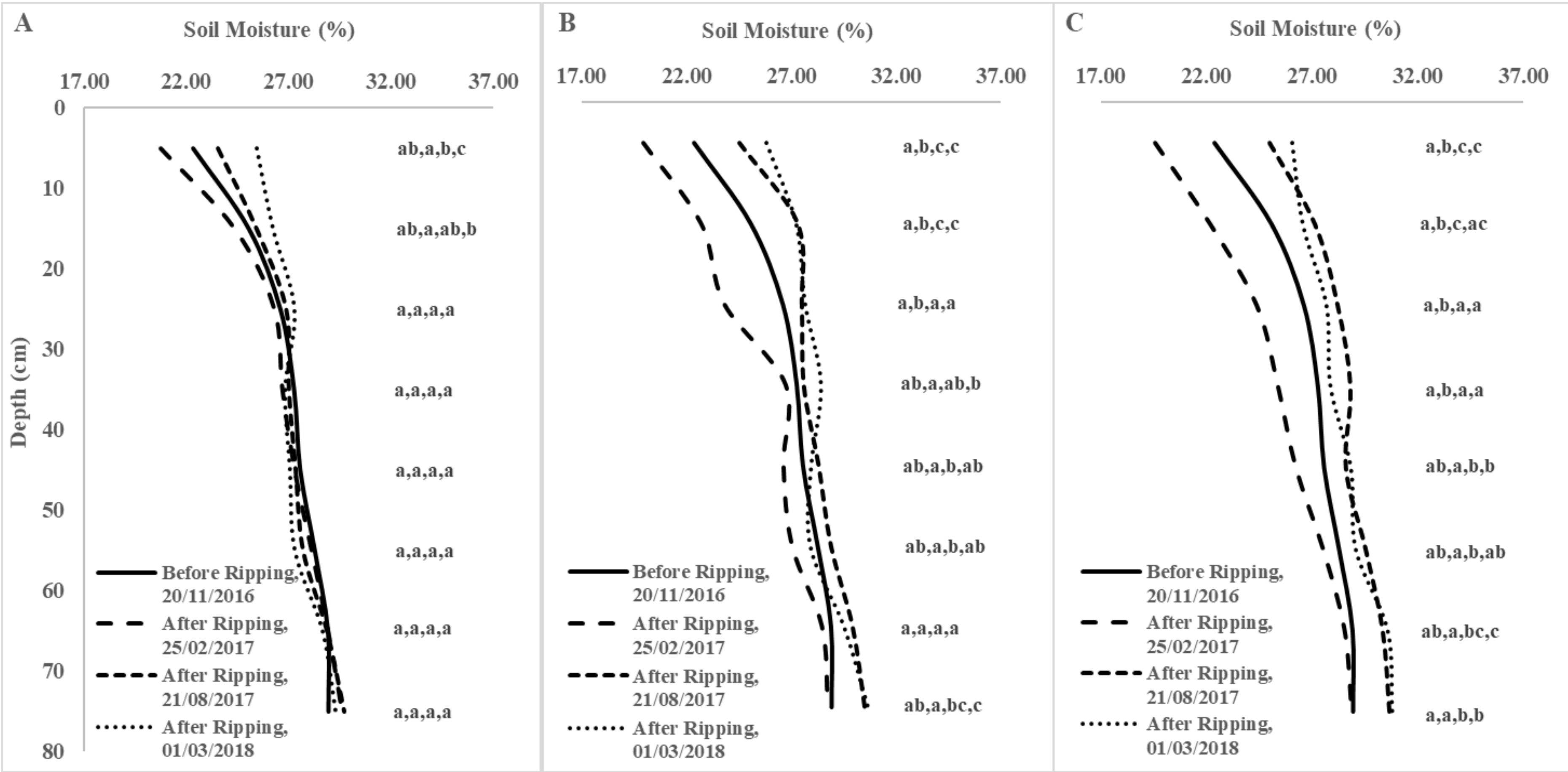

Figure 4-3: Soil moisture content (%) for control (zero ripping) (A), D1 (B), and D2 (C) ripping systems along soil depth of (0-80 cm) during the four dates at the Ag plot site. Note: variation in letters and their mismatch are evidence of the significant effect, while the similarity of letters indicates that the effect is not significant

increased significantly to 28.51% and 28.41% with an increase rate of +6% on the third and fourth date, respectively.

- **Evanslea site**

Table 4-4 shows the average moisture content for three dates along 0-80 cm at Evanslea - Black Vertosol (Roberton, 2015) and their overlaps under (D1=0-30 cm), (D2= 0-60 cm) and (C= control). From this table, it can be observed that on the first, second, and third dates, the unripped soil suffered a significant decrease in moisture content from 53.65 to 52.61 (-2%) and then to 39.51% (-26%), respectively. D1 soil moisture content also decreased significantly from 53.65 to 52.40 (-2%), then to 42.93% (-20%) on the three dates, respectively. In contrast, the initial moisture content of D2 (53.65%) increased to 54.15% on the second date (though not significant) and returned to decrease significantly to 45.01% (-16%) on the final date.

Table 4-4 also presents average moisture content of the three soil sections (D1, D2, and the C) across the study period. In comparison to the moisture content of the zero ripped soil sections, the 0-10 cm section moisture of D1 and D2 soil was not significant on the three dates. However, the moisture values of the other sections did increased compared to the corresponding sections' moisture in the control. These increases were significant along the D2 sections and in the ripped range sections only for the D1 soil. The unripped soil average moisture content for all periods and all sections increased significantly from 48.59% to 49.66% (+2%) then to 50.94% (+5%) when the level of ripping depth increased from 30 cm to 60 cm, respectively.

Table 4-4 shows each section’s moisture content along 0-80 cm for the D1, D2 and C soils and on the three dates. Figure 4-4 also shows the sections' moisture values of the D1, D2 and C soils in vertical lines commensurate with the studied soil depth (0-80 cm) and in shapes commensurate with each studied date. The water content of all control soil sections decreased on the second date. The decrease was significant for the first 40 cm and not significant for the second 40 cm. On the third date, the moisture content of all sections reduced significantly compared with the initial and second date’s moisture values. In sum, the average of all sections’ wetness decreased significantly from 53.65% to 52.61% (-2%) and then to 39.51% (-26%) on the three consecutive dates, respectively.

Table 4-4: Soil moisture content (%) at Evanslea site soil depth (0-80 cm) for three dates in the short-term and their overlaps under two deep tillage systems (D1 = 0-30 cm and D2 = 0-60 cm) with control (C = no ripping) system

Date	Date × Deep Ripping (cm)			Av. Date
	C=no ripping	D1	D2	
Sep. 2017	53.65 a	53.65 a	53.65 a	53.65 a
Nov. 2017	52.61 a,b	52.40 a	54.15 b	53.05 a
March 2018	39.51 a	42.93 b	45.01 c	42.49 b
Av. Deep Ripping	48.59 a	49.66 b	50.94 c	Tot. 49.73
Soil Depth (cm)	Soil Depth (cm) × Av. Deep Ripping (cm)			Av. Soil Depth
	C=no ripping	D1	D2	
0-10	45.04 a	44.93 a	46.28 a	45.42 a
10-20	49.79 a	53.07 b	53.26 b	52.04 b
20-30	49.63 a	51.74 b	52.61 b	51.33 b,c
30-40	49.58 a	50.01 a	52.21 b	50.60 c,d
40-50	49.11 a	49.93 a,b	51.46 b	50.17 d,e
50-60	49.00 a	49.87 a,b	50.98 b	49.95 d,e,f
60-70	48.39 a	49.05 a,b	50.38 b	49.27 e,f
70-80	48.19 a	48.67 a	50.32 b	49.06 f
Av. Deep Ripping	48.59 a	49.66 b	50.94 c	Tot. 49.73
C-Soil Depth (cm)	C - Soil Depth (cm) × Date			Av. C - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	45.49 a	44.85 a	44.78 a	45.04 a
10-20	55.20 a	52.68 b	41.49 c	49.79 b
20-30	56.40 a	54.48 b	38.00 c	49.63 b
30-40	56.66 a	54.16 b	37.91 c	49.58 b
40-50	55.05 a	54.58 a	37.70 b	49.11 b,c
50-60	54.34 a	54.10 a	38.56 b	49.00 b,c
60-70	53.31 a	53.37 a	38.50 b	48.39 c
70-80	52.77 a	52.63 a	39.16 b	48.19 c
Av. Date	53.65 a	52.61 b	39.51 c	Tot. 48.59
D1-Soil Depth (cm)	D1 - Soil Depth (cm) × Date			Av. D1 - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	45.49 a	43.16 b	46.15 a	44.93 a
10-20	55.20 a	59.00 b	45.02 c	53.07 b
20-30	56.40 a	58.00 a	40.83 b	51.74 c
30-40	56.66 a	53.00 b	40.38 c	50.01 d
40-50	55.05 a	53.00 b	41.74 c	49.93 d,e
50-60	54.34 a	53.00 a	42.28 b	49.87 d,e
60-70	53.31 a	51.00 b	42.83 c	49.05 e, f
70-80	52.77 a	49.00 b	44.23 c	48.67 f
Av. Date	53.65 a	52.40 b	42.93 c	Tot. 49.66
D2-Soil Depth (cm)	D2 - Soil Depth (cm) × Date			Av. D2 - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	45.49 a	43.19 b	50.15 c	46.28 a
10-20	55.20 a	57.84 b	46.73 c	53.26 b
20-30	56.40 a	58.52 b	42.92 c	52.61 b,c
30-40	56.66 a	57.51 a	42.47 b	52.21 c,d
40-50	55.05 a	56.26 a	43.08 b	51.46 d,e
50-60	54.34 a	55.73 a	42.88 b	50.98 e,f
60-70	53.31 a	53.15 a	44.68 b	50.38 f
70-80	52.77 a	51.00 b	47.20 c	50.32 f
Av. Date	53.65 a	54.15 a	45.01 b	Tot. 50.94

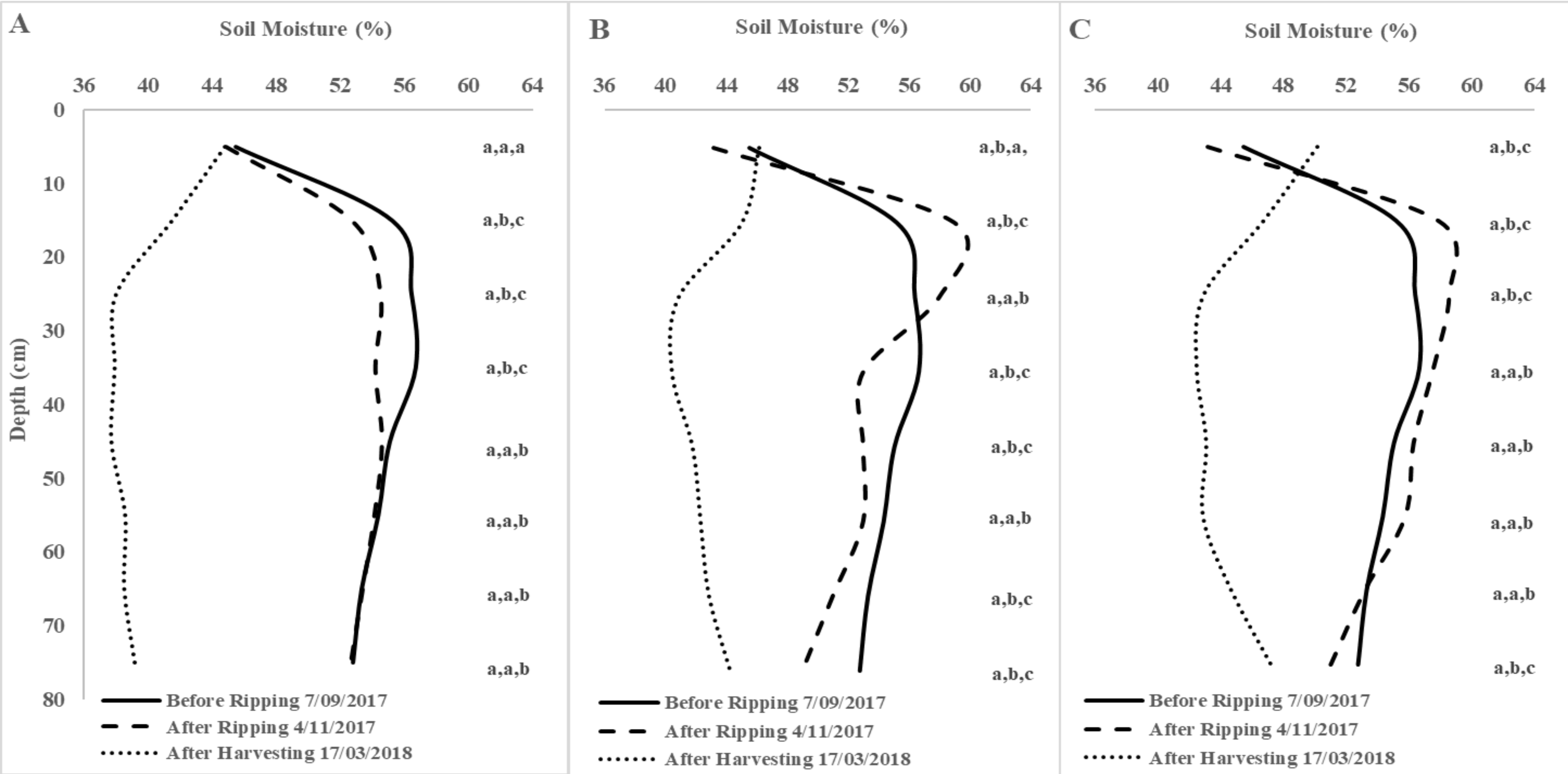

Figure 4-4: Soil moisture content (%) for control (zero ripping) (A), D1 (B), and D2 (C) ripping systems along soil depth of (0-80 cm) during the three dates at Evanslea site. Note: variation in letters and their mismatch are evidence of the significant effect, while the similarity of letters indicates that the effect is not significant

As for the D1 soil, compared to the initial values, during the second date the first upper section witnessed a significant decrease in its moisture content, while the second and third sections, which are located within the ripping zone, witnessed a significant and non-significant increase, respectively. The most of lower sections witnessed a significant decrease in their moisture content. On the third date, all of soil sections suffered a significant decline in water content compared to the first and second dates. The table concludes that the average moisture content of all total sections for this soil decreased significantly from 53.65% to 52.40% (-2%) and then to 42.93% (-20%) on the first, second and third dates, respectively. With regards to the D2 soil, most of its experienced an increase in their moisture content on the second date. The increases were significant for the three top sections and not significant for the lower sections. On the third date, all soil sections suffered from a significant decline in their water content compared to the first and second dates. The table concludes that the average of initial moisture content of all sections for this soil (53.65%) increased to 54.15% on the second date (though not significant) and to decreased significantly to 45.01% (-16%) on the third date.

From the previous two tables and figures, the average soil water content along the study period and the studied soil depth generally increased with deep ripping and the increase was directly proportional to the depth of ripping. However, the differences between the moisture content mean values were not significant at the Ag plot site whereas, at the Evanslea site the moisture difference between the three treatment soils was significant. This can be explained by the fact that ripping, as mentioned earlier, is likely to increase soil loosening and increase the particle inter-spacing within the subsoiling range, thus increasing its porosity. Increased filtration and less runoff or waterlogging may be achieved when rain falls on this soil. These soil features under a controlled traffic farming system are highly likely to increase the likelihood of the desired deep tillage targets compared to other soils subjected to random machines traffic (Raper et al., 1998).

Also, the ripped soil sections were wetter than the corresponding sections of zero ripped soils. Also, the increases in moisture content were not significant along the studied soil column at the Ag plot site while at Evanslea, the significance was see along the studied soil column in the D2 soil and within the boundary of the D1 soil.

The most plausible explanation is that rain water seeps easily into loose soil with lower bulk density, permeability and good porosity compared to dense soils where most of the rain water sits on the surface and then experiences either runoff or evaporation.

At the Ag plot site, regarding to zero ripped soil, although the water content increased during the study period, no significant difference observed between its values, whether between the soil sections or the soil column as a whole was observed. The only significant difference was in the first 10 cm, and this may be attributed to the use of a rotary hoe to prepare the sorghum and wheat seed beds before planting, causing a decrease in soil bulk density. Thus, the moisture of this loose section and compared to the first date witnessed a decrease during the second date and an increase during the third and fourth date and the reason may be to the average temperature, which was 34.7˚C, 19.7˚C and 24.9˚C (Figure 3-35), respectively.

With regards to the 0-30 cm and 0-60 cm ripped soil at Ag plot site, compared to the first date sections' moisture content, it can be seen that the significance of the difference was between the sections of the ripped range during the second, third and fourth dates. This difference was due to the decrease in moisture on the second date and the rise in moisture on the third and fourth dates. The same explanation for the zero ripped soil can be made where within the ripping range became well - porosity and aeration, so it is easy to lose its water when the temperature of surrounding atmosphere rises.

As for the soil under CTF system - Evanslea- all sections of non-ripping soil decreased in their water content after the first date. The decrease was significant for the first four sections (0-40 cm) during the second date and for all sections during the third date. This significant decrease may be attributed to the increased average temperature (27.6˚C) and lack of rainfall (85.7 mm) during the first period (from September to October 2017) (Figure 3-36). As for the second period from November 2017 to March 2018, in addition to the evaporation factor related to the high temperature (31.6˚C) and low precipitation (229.7 mm) (Figure 3-36), soil water consumption due to sorghum growth may be added to the reasons for the decreased soil moisture content.

In CTF system, soils under the D1 and D2 ripping influence showed similar moisture behaviour. For both ripped soils, on the second date, the humidity of the first 10 cm decreased significantly, followed by an increase in section moisture up to ripping depth, and what remained experienced a significant decrease. On the third date, the two ripped soils experienced a significant decrease in their sections' moisture compared to the first and second dates. This may be justified by the fact that deep tillage reduced the bulk density of the affected sections and improved their ability to absorb and store rain-water, despite its scarcity, in addition to the increase in average temperature over the first period. As for the reason for the low moisture during the second period, this may be due to the same reason as the zero ripping soil. The C, D1 and D2 soils are located in the same climatic conditions, but their water ratio increased with an increasing depth of subsoiling.

4.1.1.3 Cone index (CI)

- **Ag plot site**

Table 4-5 shows the average CI for four dates along 0-70 cm for the Ag plot Red Ferrosol soil and their overlapping under (D1=0-30 cm), (D2= 0-60 cm) and (C=no ripping). The table shows that the average cone index of the control plots on the first date, 3712 kPa, increased significantly to 4207 kPa (+13%), then decreased to 3768 kPa (though not significant), and then increased significantly to 3983 kPa (+7%), on the second, third and fourth dates, respectively. The average C1 of D1 plots on the first date 3712 kPa declined significantly to 3361 kPa (-9%), 2728 kPa (-27%), and then to 2787 kPa (-25%) on the second, third and fourth dates, respectively. The D2 cone index story was the same, where the plots' average CI on the first date 3712 kPa decreased significantly to 3080 kPa (-17%), 2577 kPa (-31%), and then to 2519 kPa (-32%) on the second, third and fourth dates, respectively. Table 4-5 shows that over the periods of deep tillage, the resistance to penetration of both D1 and D2 soil decreased significantly compared to the corresponding values of zero ripped soil.

The table also includes the CI values of the three soil sections to a depth of 70 cm. When looking at the soil section values in Table 4-5, it appears that the CI number increases with increasing depth regardless of the tillage system applied. Compared to the Control soil sections, table 4-5 shows that both D1 and D2 reduced the all soil sections' penetration resistance however, the significant difference was seen up to 50 cm. It appears that, across the study period and study depth of 70 cm, the average Control soil CI of 3918 kPa decreased significantly to 3147 kPa (-20%) and then to

2972 kPa (-24%) when the penetration level of the single tine ripper increased from 30 cm to 60 cm, respectively. The sections' CI values for each soil over the studied periods and up to 70 cm are also shown in detail in table 4-5.

To give a clear visualization when reviewing the results, soil sections numbers (values) were converted into vertical, curved, dashed and continuous lines of 70 cm depth (Figure 4-5). For zero ripped soil, compared to the initial CI, the 0-10 cm soil section’s CI, 1780 kPa, decreased significantly to 899 kPa (-49%), then to 1060 kPa (-40%), and then to 1151 kPa (-35%) during the second, third and fourth dates, respectively. The average CI for the rest of the soil sections increased significantly during the subsequent studied dates compared with the first date. The average CI of total studied soil sections on the first date, 3712 kPa, increased to 4207 kPa (+13%) then to 3768 kPa and then to 3983 kPa (+7%) on the second, third and fourth dates, respectively. The increase was significant except on the third date where it was not significant.

For both D1 and D2 soils, in comparison with the first date, at the second date, the soil sections at the ripped level experienced a significant decrease in CI values while the soil sections below this level experienced an increase but not significant. On the third and fourth dates, all soil sections experienced a decrease in CI values compared to the initial date, and the decrease was significant - up to 50 cm in depth. In general, the average soil CI of all D1 soil sections on the first date 3712 kPa decreased significantly to 3361 kPa (-9%) then to 2728 kPa (-27%) and then to 2787 kPa (-25%) on the second, third and fourth dates, respectively. Likewise, the mean soil CI of the all D2 soil sections on the first date, 3712 kPa, decreased significantly to 3080 kPa (-17%) then to 2577 kPa (-31%) and then to 2519 kPa (-32%) on the second, third and fourth dates, respectively. The table shows that the percentage of decrease of total soil CI increased with increasing ripping depth and age, and the decreasing percentage of both soil strength increased on the third and fourth dates compared to the second date.

Table 4-5: Soil cone index (kPa) at Ag plot site soil depth (0-70 cm) and for four dates in the short-term and their overlaps under two deep tillage systems (D1 = 0-30 cm and D2 = 0-60 cm) with control (C = no ripping) system

Date	Date × Deep Ripping (cm)			Av. Date
	C=no ripping	D1	D2	
Nov. 2016	3712 a	3712 a	3712 a	3712 a
Feb. 2017	4207 a	3361 b	3080 b	3549 a
Aug. 2017	3768 a	2728 b	2577 b	3024 b
March 2018	3983 a	2787 b	2519 b	3097 b
Av. Deep Ripping	3918 a	3147 b	2972 b	Tot. 3346
Soil Depth (cm)	Soil Depth (cm) × Av. Deep Ripping (cm)			Av. Soil Depth
	C=no ripping	D1	D2	
0-10	1223 a	928 a	1228 a	1126 a
10-20	3313 a	1823 b	1881 b	2339 b
20-30	4108 a	2464 b	2225 b	2932 c
30-40	4482 a	3457 b	2969 b	3636 d
40-50	4698 a	4027 b	3355 c	4026 e
50-60	4696 a	4465 a	4312 a	4491 f
60-70	4904 a	4866 a	4837 a	4869 g
Av. Deep Ripping	3918 a	3147 b	2972 b	Tot. 3346

C-Soil Depth (cm)	C - Soil Depth (cm) × Date				Av. C - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	1780 a	899 b	1060 b	1151 b	1223 a
10-20	3173 a,b	3659 a	3348 a,b	3072 b	3313 b
20-30	3516 a	4682 b	4176 c	4059 c	4108 c
30-40	3758 a	5474 b	4079 a	4615 c	4482 d
40-50	4194 a	5219 b	4520 a,c	4857 c,b	4698 d,e
50-60	4534 a	4572 a	4493 a	5185 b	4696 d,e
60-70	5029 a	4942 a	4703 a	4942 a	4904 e
Av. Date	3712 a	4207 b	3768 a	3983 c	Tot. 3918
D1-Soil Depth (cm)	D1 - Soil Depth (cm) × Date				Av. D1 - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	1780 a	614 b	700 b	618 b	928 a
10-20	3173 a	1872 b	1028 c	1219 c	1823 b
20-30	3516 a	2764 b	1735 c	1840 c	2464 c
30-40	3758 a	4251 b	3083 c	2734 c	3457 d
40-50	4194 a	4373 a	3630 b	3910 a,b	4027 e
50-60	4534 a	4568 a	4408 a	4351 a	4465 f
60-70	5029 a	5087 a	4509 b	4839 a,b	4866 g
Av. Date	3712 a	3361 b	2728 c	2787 c	Tot. 3147
D2-Soil Depth (cm)	D2 - Soil Depth (cm) × Date				Av. D2 - Soil Depth
	Nov. 2016	Feb. 2017	Aug. 2017	March 2018	
0-10	1780 a	972 b	1154 b	1005 b	1228 a
10-20	3173 a	1881 b	1257 c	1213 c	1881 b
20-30	3516 a	1955 b	1602 b	1826 b	2225 c
30-40	3758 a	3405 a	2203 b	2510 b	2969 d
40-50	4194 a	3539 b	3051 b,c	2634 c	3355 e
50-60	4534 a,b	4853 a	4059 b,c	3800 c	4312 f
60-70	5029 a	4955 a	4715 a	4647 a	4837 g
Av. Date	3712 a	3080 b	2577 c	2519 c	Tot. 2972

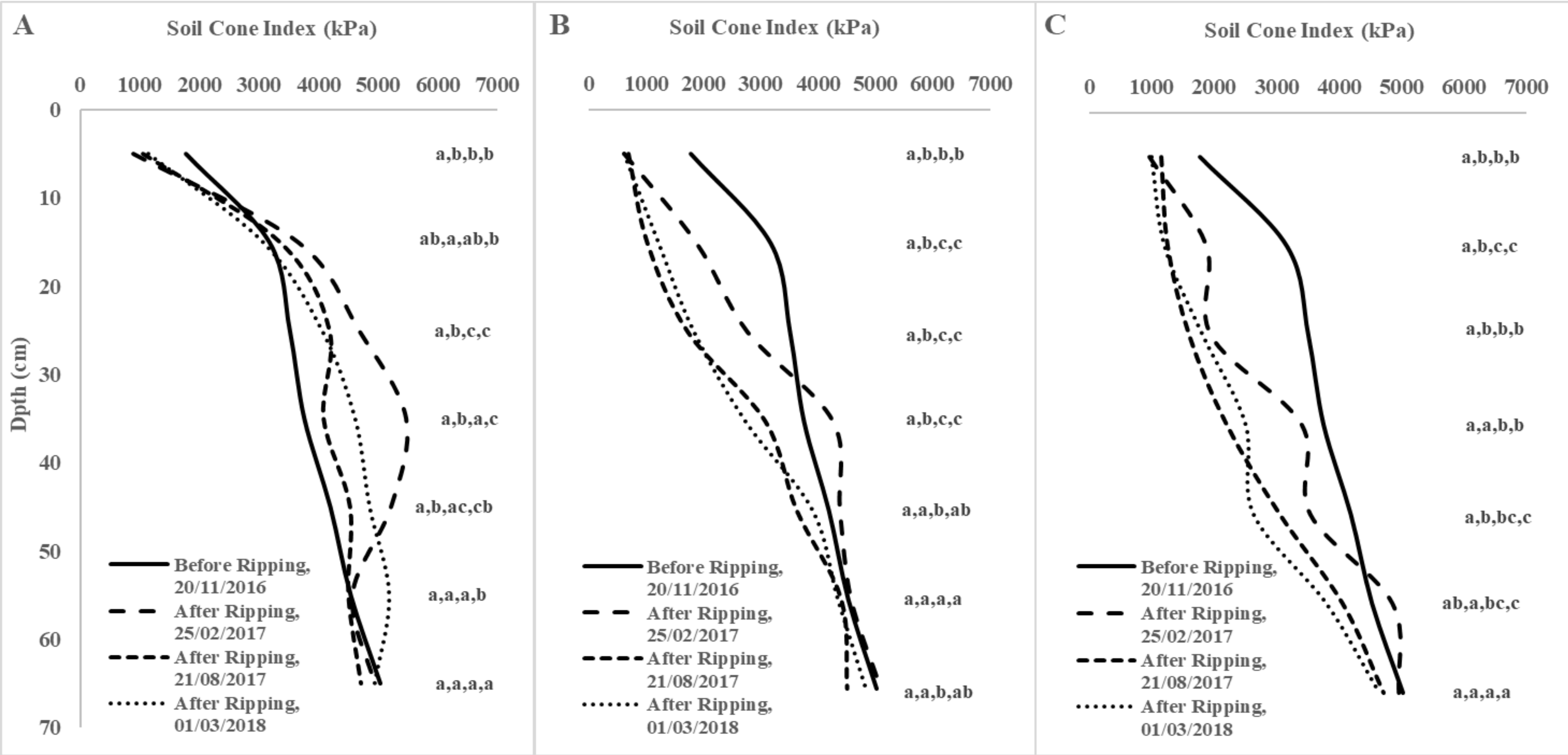

Figure 4-5: Soil cone index (kPa) for control (zero ripping) (A), D1 (B), and D2 (C) ripping systems along soil depth of (0-70 cm) during the four dates at Ag plot site. Note: variation in letters and their mismatch are evidence of the significant effect, while the similarity of letters indicates that the effect is not significant

- **Evanslea site**

Table 4-6 shows the average cone index for three dates along 0-70 cm for Evanslea - Black Vertosol and their overlapping under (D1=0-30 cm), deep (D2= 0-60 cm) and no or zero ripping (C= control). The table shows that the average CI of the control plots on the first date, 1165 kPa, non-significant increased to 1187 kPa and then increased significantly to 2692 kPa (+131%), on the second and third dates, respectively. The average of D1 plots' initial CI (before ripping) on the first date 1165 kPa decreased significantly to 935 kPa (-20%), and then increased significantly to 1583 kPa (+36%) on the second and third dates, respectively. The CI story for D2 was the same as D1, where the plots' average CI on the first date, 1165 kPa, decreased significantly to 534 kPa (-54%), and then increased significantly to 1336 kPa (+15%) on the second and third dates, respectively. It is very clear that the average initial CI on the second and third dates decreased significantly for ripped soils compared to the Control soil.

Table 4-6 also contains the average CI of the D1, D2 and the C soil sections across the study period to the depth of 70 cm. It shows that, despite the differences in their CI value, the D1, D2 and the C soils agree that the shallow sections have a lower CI value than the deep ones. Furthermore, compared to the zero ripped soil sections CI values, both the 0-30 and 0-60 cm ripping treatments reduced soil sections' penetration resistance along of 70 cm significantly, except for the section of 0-10 cm where the decrease was not significant. Finally, the average CI of the zero ripped soil over the study period and sections decreased significantly from 1681 kPa to 1228 kPa (-27%) and then to 1012 kPa (-40%) when the level of tine ripping penetration depth increased from zero to 30 cm and then to 60 cm, respectively.

the same as D1, where the plots' average CI on the first date, 1165 kPa, decreased significantly to 534 kPa (-54%), and then increased significantly to 1336 kPa (+15%)

Table 4-6 also shows each soil section's CI along 0-70 cm for each soil separately and on the three dates. Figure 4-6 shows the CI values of each soils' sections in vertical line forms that represent studied soil depth (0-70 cm) and in shapes representing each studied date to give a clear visualization when reviewing the results. On the second date, the zero ripped soil sections experienced a slight and non-significant increase and decrease in their CI values across the depth of the study. However, on the third

Table 4-6: Soil cone index (kPa) at Evanslea site soil depth (0-70 cm) for three dates for the short-term and their overlaps under two deep tillage systems (D1 = 0-30 cm and D2 = 0-60 cm) with control (C = no ripping) system

Date	Date × Deep Ripping (cm)			Av. Date
	C=no ripping	D1	D2	
Sep. 2017	1165 a	1165 a	1165 a	1165 a
Nov. 2017	1187 a	935 b	534 c	885 b
March 2018	2692 a	1583 b	1336 c	1870 c
Av. Deep Ripping	1681 a	1228 b	1012 c	Tot. 1307
Soil Depth (cm)	Soil Depth (cm) × Av. Deep Ripping (cm)			Av. Soil Depth
	C=no ripping	D1	D2	
0-10	406 a	298 a	297 a	334 a
10-20	1234 a	737 b	693 b	888 b
20-30	1482 a	915 b	649 c	1015 b
30-40	1802 a	1265 b	726 c	1264 c
40-50	2012 a	1467 b	1261 b	1580 d
50-60	2188 a	1754 b	1591 b	1844 e
60-70	2647 a	2161 b	1864 c	2224 f
Av. Deep Ripping	1681 a	1228 b	1012 c	Tot. 1307
C-Soil Depth (cm)	C - Soil Depth (cm) × Date			Av. C - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	382 a	354 a	481 a	406 a
10-20	1075 a	1056 a	1570 b	1234 b
20-30	990 a	1053 a	2403 b	1482 c
30-40	1102 a	1120 a	3183 b	1802 d
40-50	1220 a	1216 a	3599 b	2012 e
50-60	1480 a	1425 a	3658 b	2188 f
60-70	1909 a	2083 a	3949 b	2647 g
Av. Date	1165 a	1187 a	2692 b	Tot. 1681
D1-Soil Depth (cm)	D1 - Soil Depth (cm) × Date			Av. D1 - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	382 a	233 a	278 a	298 a
10-20	1075 a	256 b	880 a	737 b
20-30	990 a	745 b	1009 a	915 c
30-40	1102 a	1097 a	1596 b	1265 d
40-50	1220 a	1143 a	2039 b	1467 e
50-60	1480 a	1357 a	2426 b	1754 f
60-70	1909 a	1717 a	2856 b	2161 g
Av. Date	1165 a	935 b	1583 c	Tot. 1228
D2-Soil Depth (cm)	D2 - Soil Depth (cm) × Date			Av. D2 - Soil Depth
	Sep. 2017	Nov. 2017	March 2018	
0-10	382 a	150 b	360 a,b	297 a
10-20	1075 a	222 b	782 c	693 b
20-30	990 a	257 b	701 c	649 b
30-40	1102 a	223 b	854 c	726 b
40-50	1220 a	643 b	1919 c	1261 c
50-60	1480 a	1070 b	2222 c	1591 d
60-70	1909 a	1171 b	2511 c	1864 e
Av. Date	1165 a	534 b	1336 c	Tot. 1012

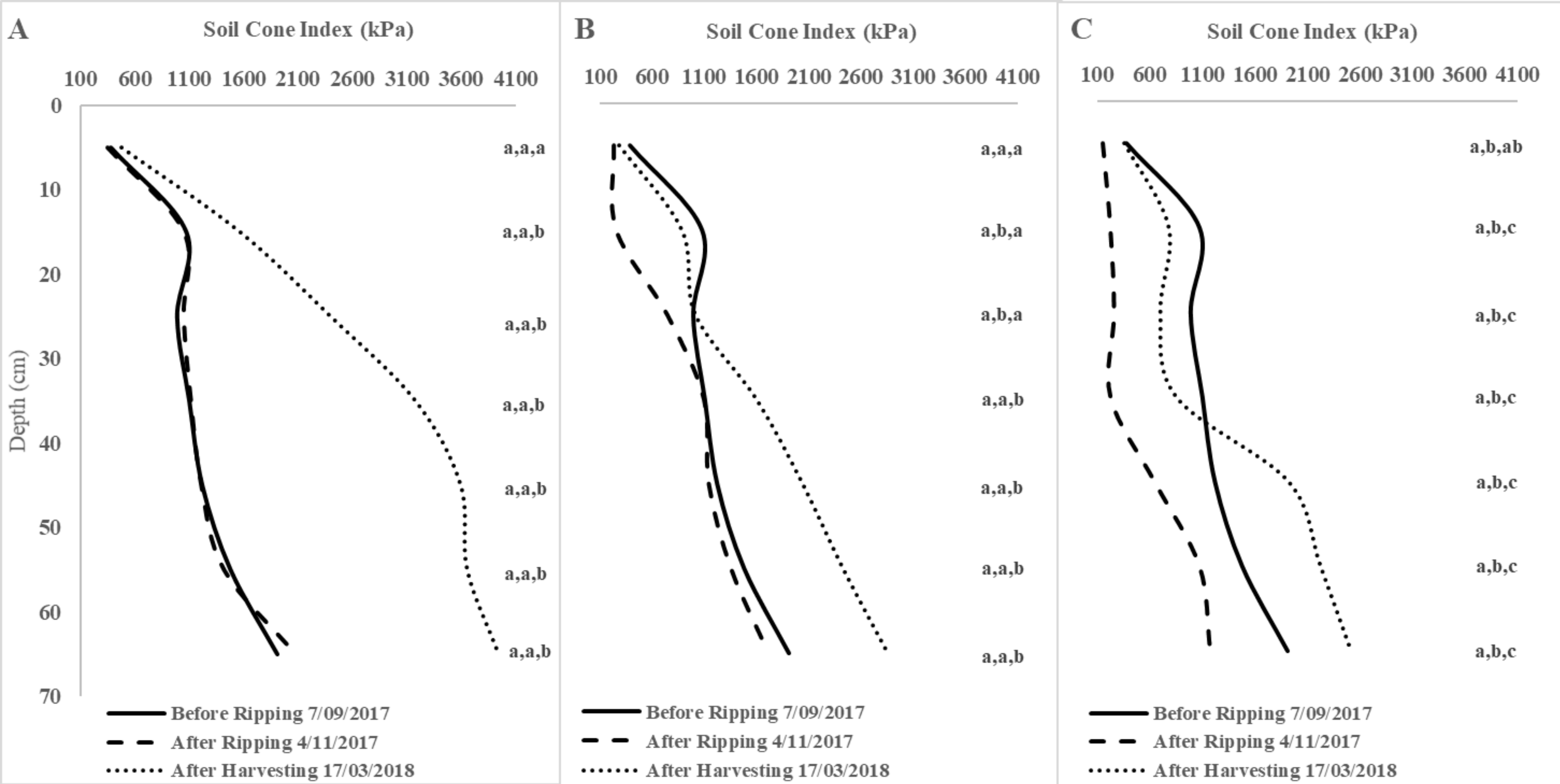

Figure 4-6: Soil cone index (kPa) for control (zero ripping) (A), D1 (B), and D2 (C) ripping systems along soil depth of (0-70 cm) during the three dates at Evanslea site. Note: variation in letters and their mismatch are evidence of the significant effect, while the similarity of letters indicates that the effect is not significant

date, except the first 10 cm, where the increase was not significant, all sections cone index values increased significantly compared to the first and second date cone index values. In sum, the average CI of all studied soil sections on the first date, 1165 kPa, increased to 1187 kPa (+2%) and then to 2692 kPa (+131%) on the second and third dates, respectively. The least significant difference (LSD) was not significant on the second date, and significant on the third date.

As for the D1 soil compared to the initial CI values, on the second date, the first upper soil section experienced a decrease in its CI value (though not significant), while the second and third soil sections, which are located in the ripping zone, experienced a significant decrease -76% and -25%, respectively. Though not significant, most of the lower sections experienced a decrease in their CI value. On the third date, compared to the second date CI values, all of soil sections suffered from a significant increase in CI except for the section of 0-10 cm where the increase was not significant. Table 4-6 shows that the average CI of all sections for this soil on the first date, 1165 kPa, decreased significantly to 935 kPa (-20%), and then increased significantly to 1583 kPa (+36%) on the second and third date, respectively.

Regarding the D2 soil, compared to the initial CI values, most of its sections experienced a significant decrease in their CI on the second date. On the third date, compared to the second date’s CI values, all soil sections suffered from a significant increase in their CI except for the 0-10 cm section where the increase was not significant. The average CI of all sections for this soil on the first date, 1165 kPa, decreased significantly to 534 kPa (-54%), and then increased significantly to 1336 kPa (+15%) on the second and third dates, respectively. From Figure 4-6, it is very clear that the ripping rang soil sections on the third date were less than the initial CI values. As well, from Table 4-6 and Figure 4-6, it appears that the D1, D2 and C soils experienced an increase in CI values after harvesting (the third date) which exceeds even the first soil values however, the average CI of D1 (1583 kPa) and D2 (1336 kPa) were lower than the Control soil (2692 kPa) by 42% and 50%, respectively.

After displaying the results for both sites through the two tables and figures, it is say that deep ripping over the study periods and a study depths had a significant effect, decreasing the average of the soil cone index. The size of this reduction increased with the increasing level of ripping. The most likely explanation is the percent of soil moisture content. Deep tillage will, most likely, increase the spacing between soil particles, increase water capacity and content, reduce soil moisture tension, reduce liquid pressure that fills the pores, and decrease the soil internal friction angle and, as a result, soil resistance to penetration will decrease.

A review of the results also shows an increase in the three deep soil sections' resistance to cone penetration compared to the shallow soil sections. This may be because soil bulk density, particle proximity and clay percentage increase with increasing section depth, making it highly likely that the cone will face difficulty penetrating the soil.

Also, Evanslea’s CI values are lower than the Ag plot site’s values. This may be attributed to: 1) the farming system which was CTF for Evanslea and RTF for the Ag plot site, increasing soil bulk density and decreasing moisture content, both of which affect soil penetration resistance and 2) the clay ratio which was 69.06% for the Ag plot site and 64.79% for the Evanslea site which may also increase the penetration resistance value. For clayey soils, the penetration resistance increases by increasing the percentage of clay (Ayers & Perumpral, 1982).

At the Ag plot site, the reason for the significant low in the first 10 cm CI of control soil on the second, third and the fourth dates compared with the first date may be due to the use of a rotary hoe to prepare the sorghum and wheat seed beds before planting, causing a decrease in density. The falloff in total rainfall and rise in average temperature during the first period summer months (December 2016 to February 2017) and third period (December 2017 to February 2018), which were 33.8˚C, 140.5 mm and 28.2˚C, 229.6 mm, respectively (Figure 3-35), are among the most common reasons for increasing soil CI value significantly. While, on the second and fourth periods, the seed bed preparation, seeding, and manual crop servicing and harvesting practices are the most common reasons for the significant increase in soil CI value.

With regards to the ripped soil at the Ag plot site, compared to the first date sections' CI values, although the water level of the D1 and D2 loosened soil sections decreased significantly during first period (the second date), the resistance to cone penetration decreased significantly. This may be due to the significant decline in its bulk density due to deep ripping and the accompanying consequences mentioned earlier. On the third date (second period) and fourth date (third period), most of D1 and D2 soils sections experienced a significant decrease in their resistance to cone penetration, and the significant, high humidity may have played a major role, along with the stability and good porosity and aeration of the soil.

As for the soil under Evanslea's controlled traffic farming system, the reason for the high resistance to cone penetration by all soil sections except the 0 -10 cm on the third date (the second period from November 2017 to March 2018) may be due to the rise in average temperature (31.6˚C), lack of precipitation (229.9 mm) (Figure 3-36), and frequency of fertilisation, crop servicing and harvesting operations which in turn lead to soil shrinkage and increased soil bulk density. Moreover, according to J.M. Bennett (personal communication, October 19, 2018) the most likely possibility is that the Vertosols may become frictional and behave like sandy soils when they dry out, and as soften and behave like a clay soil when moistened. This may provide a convincing answer for the high soil penetration resistance.

As for the D1 and D2 soils at the Evanslea site, the reason for the significant decrease in CI value for the sections falling in the ripping depth on the second date may be attributed to the increased moisture content due to the low soil bulk density, causing an increase in soil porosity and, consequently, an increase in the amount of water filtered into the soil increasing water storage capacity. As for the third date, the reason for the high CI reading value for all soil sections except the first 10 cm, may be the high temperatures that led to the evaporation of water from the loose-well-ventilated soil layers, thereby increasing the soil particle convergence and friction force with the cone surface as result of increasing the soil external friction angle.

From this analysis, it is possible to see that deep ripping reduced the soil cone index values significantly in both farming systems. It can also be seen that the moisture of ripped soil has a major role in reducing or raising soil penetration resistance.

4.1.2 Crop parameters

Plant response rate is an indicator that may be reliable, acceptable and categorical when assessment agricultural operations in addition to physical soil changes. Accordingly, the yield of grain and dry biomass as well as to the index of harvest were the studied properties of Ag plot site crops (sorghum and wheat) and Evanslea site sorghum crop.

4.1.2.1 Grain yield

- **Ag plot site**

Sorghum grain yield

Table 4-7: Effect of ripping depths (C= no ripping, D1= 0-30 cm, and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 140 kg N/ha) with their overlap on sorghum grain yield (kg/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)			Av. Ripping depth (cm)
	0		140	
No ripping	4097, a		4388, a	4243, a
0-30	4575, a		4964, b	4770, b
0-60	4716, a		5360, b	5038, c
Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	4097, a	4575, b	4716, b	4463, a
140	4388, a	4964, b	5360, c	4904, b

Table 4-7 shows the effect of ripping depths (C, D1, and D2) and N fertiliser rates (0 kg/ha and 140 kg/ha) with their interaction on sorghum grain yield. The statistical analysis shows that deep ripping had a significant effect on the productivity of sorghum grain as the average yield increased significantly from 4243 kg/ha to 4770 kg/ha (+12%), and then 5038 kg/ha (+19%) when the subsoiling depth increased from 0 cm to 30 cm then to 60 cm, respectively.

From Table 4-7, Appendix F.1 and its subdivisions, the fertiliser was also significant in raising sorghum grain productivity, as adding 140 kg N/ha achieved a grain production of 4904 kg/ ha with an increase of 10% compared to unfertilised treatment which had a yield rate of 4463 kg/ha.

The interaction between deep ripping depths and fertilisation rates had a significant effect on sorghum grain yield however, from the table and appendices, both applying N at 0 kg/ha and 140 kg/ha on unripped soils, did not have any significant effect on the grain yield. The overlap between the D2 and 140 kg N/ha rate was superior, achieving the highest grain yield (5360 kg/ha) while the lowest grain yields resulted from the interaction of zero ripping with 0 kg N /ha rate (4097 kg/ha).

Wheat grain yield

Table 4-8: Effect of ripping depths (C= no ripping, D1= 0-30 cm, and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 110 kg N/ha) with their overlap on wheat grain yield (kg/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)			Av. Ripping depth (cm)
	0	110		
No ripping	1613, a	1828, a		1721, a
0-30	1803, a	2115, b		1959, b
0-60	2083, a	2419, b		2251, c
Fertiliser Rate (kg N/ha)	**Ripping Depth (cm)**			**Av. Fertiliser rate (kg N/ha)**
	No ripping	0-30	0-60	
0	1613, a	1803, a	2083, b	1833, a
110	1828, a	2115, b	2419, c	2121, b

Table 4-8 with shows the effect of ripping depths (C, D1, and D2) and N fertiliser rates (0 kg/ha and 110 kg /ha) with their overlapping on wheat grain yield. From Table 4-8, Appendix F.6 and its subdivisions, it appears that increasing the single-tine ripper depth had a significant effect on the average wheat grain yield. When the depth changed from zero to 30 cm, and then to 60 cm, wheat grain yield jumped from 1721 kg/ha to 1959 kg/ha (+14) and then to 2251 kg/ha (+31), respectively.

Similarly, the two fertilisation rate options had a significant effect on wheat grain yield quantity which increased from 1833 kg/ha to 2121 kg/ha (+16%) when the N dose changed from 0 kg/ha to 110 kg/ha, respectively.

As for the interaction between C, D1 and D2 and the quantity of N in kg per hectare, the table shows that applying N at 0 kg/ha and 110 kg/ha on unripped soils, did not have any significant effect on the grain yield. While, on ripped soils, the interaction had a significant effect on wheat grain productivity. The highest wheat grain yield was 2419 kg/ha, which resulted from overlapping of 0-60 cm ripping depth with fertiliser rate of 110 kg N/ha, while the overlapping between the no-ripping system with no fertiliser achieved the lowest yield of wheat grain, which was 1613 kg/ha.

- **Evanslea site**

Sorghum grain yield

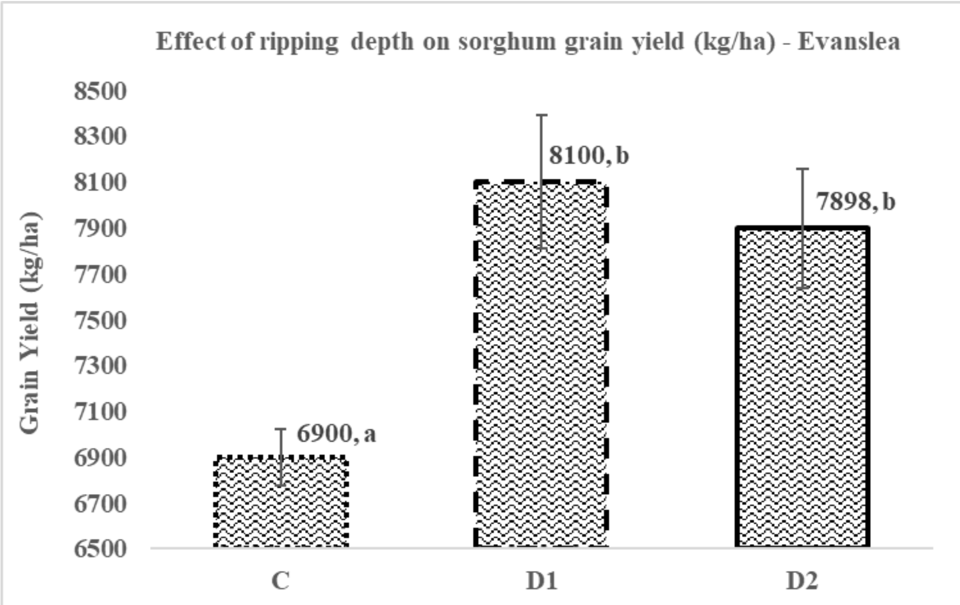

Figure 4-7: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) on sorghum grain yield (kg/ha), Evanslea site

Figure 4-7 shows the effect of ripping depths (C, D1 and D2) on sorghum grain yield. The results show that the D1 and D2 ripping systems had a significant effect on increasing sorghum grains yield. In comparison, the zero ripped soil experienced grain productivity of 6900 kg/ha, 0-30 cm ripping achieved grain productivity of 8100 kg/ha with a rate increase of 17%, while the 0-60 cm ripping achieved grain productivity of 7898 kg/ha with 14% as an increase rating. Although the D1 plots' average grain production was more than the D2 plots' productivity, the achieved production increase was not significant.

Discussion

At the Ag plot site, the soil was considered compacted according to the soil bulk density and cone index results. Deep ripping may have led to reduced soil bulk density, soil strength and waterlogging, improved soil drainage and aeration, and the provision of a warm, suitable bed for seed growth which played a key role in increasing germination (the seedling emergence), root density and elongation, plant population, thus higher grain yield production.

At the Evanslea site, the soil data shows that the ripper reduced soil bulk density within the ripping boundary. So, in addition to the Ag plot loosened soil high grain yield reasons, deep ripping at this site may have induced sorghum root penetration far into the soil, especially when temperatures were high and rain-water lacking. Thus, the possibility of reaching and maintaining water and nutrients necessary for plant growth may be almost certain compared to those growing plants in control soils that may suffer from stress and thirst.

With regards to the N fertilisation role and increased cereal production, in most soils devoted to crop growing, N may be the first element lost, through plant consumption, soil penetration or emitted into the atmosphere in the form of N_2O. N availability, through fertilisation, could maintain soil fertility and enhance nutrients, amino and organic acids which in turn increase root growth, leaf size and may accelerate the flowering date, thus improving yield quantity and quality.

4.1.2.2 Dry biomass yield

- **Ag plot site**

Sorghum dry biomass yield

Table 4-9: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 140 kg N/ha) with their overlap on sorghum dry biomass yield (kg/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)		Av. Ripping depth (cm)
	0	140	
No ripping	10126, a	10950, b	10538, a
0-30	11195, a	12671, b	11933, b
0-60	11718, a	13269, b	12494, c

Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	10126, a	11195, b	11718, b	11013, a
140	10950, a	12671, b	13269, b	12297, b

Table 4-9 with Appendix F.2 and subdivisions shows the effect of ripping depths (C, D1 and D2) and N fertiliser rates (0 kg/ha and 140 kg/ha) with their overlapping on the sorghum dry biomass yield. The data shows that deep ripping had a significant effect on the dry biomass production of sorghum as the dry matter increased significantly from 10538 kg/ha to 11933 kg/ha (+13%) and then 12494 kg/ha (+19%), when the deep tillage depth increased from 0 cm to 30 cm then to 60 cm, respectively. The data also shows that the increased N application (as urea) from 0 kg/ha to 140 kg/ha led to a significant increase in sorghum dry matter from 11013 kg/ha to 12297 kg /ha with an increase rate of 12%.

As for the interaction between deep tillage systems and N rates, the table shows that the effect of the C, D1 and D2 ripping systems on fertilised and non-fertilised plots' dry biomass production was significant. The effect of fertilised and non-fertilised treatments on dry biomass yield for plots under the D1 and D2 ripping was not significant. In sum, the interaction between ripping of 0-60 cm and N application of 140 kg/ha achieved the highest dry biomass yield (13269 kg/ha) while the interaction between no ripping and no N fertiliser application achieved the lowest dry biomass yield (13269 kg/ha).

Wheat dry biomass yield

Table 4-10: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 110 kg N/ha) with their overlap on wheat grain yield (kg/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)			Av. Ripping depth (cm)
	0		110	
No ripping	3467, a		4493, b	3980, a
0-30	4380, a		5380, b	4880, b
0-60	4787, a		5960, b	5373, c
Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	3467, a	4380, b	4787, b	4211, a
110	4493, a	5380, b	5960, b	5278, b

Table 4-10 shows the effect of ripping depths (C, D1 and D2) and N fertiliser rates (0 kg/ha and 110 kg/ha) with their overlapping on wheat dry biomass yield. It appears from the table and appendices that increasing ripper depth from 0 cm to 30 cm and then to 60 cm led to a significant increase in wheat dry matter from 3980 t kg/ha o 4880 kg/ha (+23%) and then to 5373 kg/ha (+35%), respectively.

From Table 4-10, Appendix F.7 and its subdivisions, increasing N application from 0 kg /ha to 110 kg /ha led to a significant increase in wheat dry biomass from 4211 to 5278 kg /ha, 25% increase.

As for the overlapping between deep tillage systems and N application rates, the table shows that the effect of the C, D1 and D2 ripping systems on fertilised and non-fertilised plots' dry biomass production was significant. The effect of fertilised and non-fertilised treatments on wheat dry biomass yield for plots under the D1 and D2 ripping systems was not significant. Last, the interaction between ripping at 0-60 cm and N application of 110 kg/ha achieved the highest dry biomass yield (5960 kg/ha) while the overlapping between no-ripping system with no N fertiliser application achieved the lowest yield of wheat dry biomass, which was 3467 kg/ha.

- **Evanslea site**

Sorghum dry biomass

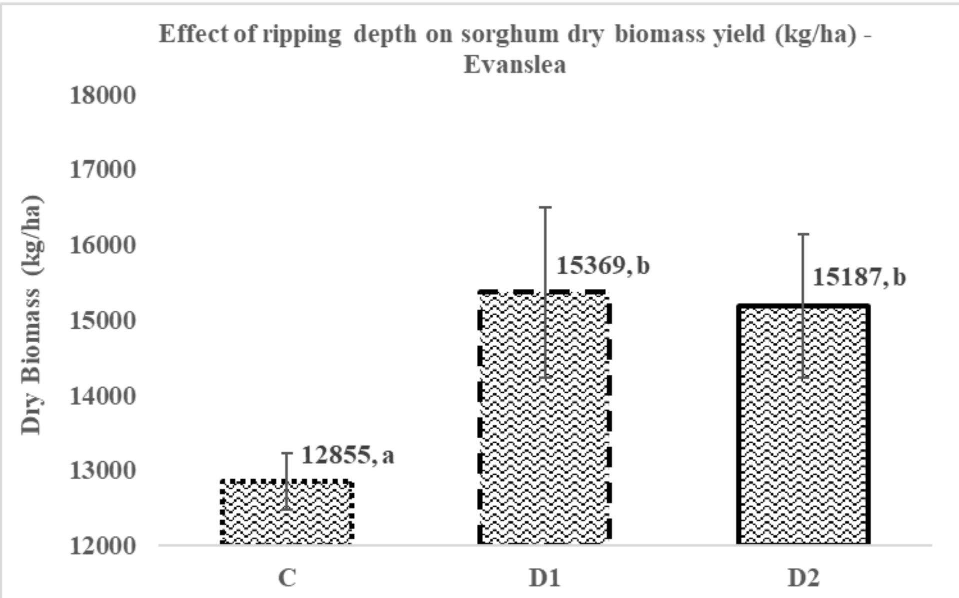

Figure 4-8: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) on sorghum dry biomass yield (kg/ha), Evanslea site

Figure 4-8 shows the effect of ripping depths (C, D1 and D2) on sorghum dry biomass yield. The D1 and D2 ripping systems had a significant increase on sorghum dry biomass yield. The shift from no ripping to ripping to a depth of 30 cm and then to a depth of 60 cm made the dry biomass production values of sorghum increase from 12855 kg/ha to 15369 kg/ha and then to 15187 kg/ha with 20 and 18 as percentage increase, respectively. The average of 0-30 cm subsoiling trials' productivity was higher than those of 0-60 cm trials, however the increase was not significant.

Discussion

The data presented in the tables, appendices and the figure show that deep ripping was successful in increasing plant biomass. The reasons mentioned for increased grain productivity may play the same role in increasing vegetation growth. In short, deep tillage resulted in improved soil bulk density and structure, which in turn increased water storage capacity and stimulated horizontal and vertical plant root growth allowing the roots to reach water at a time of scarcity. Soil water is a prerequisite for photosynthesis, so its availability means increased plant growth.

Regarding to N fertilisation and increased sorghum biomass; N is considered one of the main and essential elements required by plants, in addition to oxygen (O), hydrogen (H) and carbon (C), facilitating the manufacture of food through photosynthesis. Soil is the main source of N, while water and air are the main sources of O, H and C. Hence, N fertiliser plays a key role in increasing plant growth (Khamis, Lamaze, Lemoine, & Foyer, 1990; Sage & Pearcy, 1987; Terashima & Evans, 1988).

4.1.2.3 Harvest index (HI)

- **Ag plot site**

Sorghum harvest index

Table 4-11: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 140 kg N/ha) with their overlap on sorghum harvest index (%), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)		Av. Ripping depth (cm)
	0	140	
No ripping	40.51, a	40.08, a	40.30, a
0-30	40.86, a	39.16, a	40.01, a
0-60	40.30, a	40.39, a	40.34, a

Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	40.51, a	40.86, a	40.30, a	40.56, a
140	40.08, a	39.16, a	40.39, a	39.88, a

Table 4-11 shows the effect of ripping depths (C, D1 and D2) and urea fertiliser rates (0 kg N/ha and 140 kg N/ha) with their overlapping on sorghum HI. The results of the statistical analysis alongside the table data, as well as on the tops of the columns of Appendix F.3 and its subdivisions, show that both deep tillage and applied N levels, as well as their interactions, did not have a significant effect on the HI ratio.

Wheat harvest index

Table 4-12: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 110 kg N/ha) with their overlap on wheat harvest index (%), Ag plot site

<table>
<tr><td rowspan="2">Ripping Depth (cm)</td><td colspan="4">Fertiliser Rate (kg N/ha)</td><td rowspan="2">Av. Ripping depth (cm)</td></tr>
<tr><td colspan="2">0</td><td colspan="2">110</td></tr>
<tr><td>No ripping</td><td colspan="2">47.18, a</td><td colspan="2">40.72, a</td><td>43.95, a</td></tr>
<tr><td>0-30</td><td colspan="2">41.66, a</td><td colspan="2">39.43, a</td><td>40.55, a</td></tr>
<tr><td>0-60</td><td colspan="2">43.58, a</td><td colspan="2">40.64, a</td><td>42.11, a</td></tr>
<tr><td rowspan="2">Fertiliser Rate (kg N/ha)</td><td colspan="4">Ripping Depth (cm)</td><td rowspan="2">Av. Fertiliser rate (kg N/ha)</td></tr>
<tr><td>No ripping</td><td colspan="2">0-30</td><td>0-60</td></tr>
<tr><td>0</td><td>47.18, a</td><td colspan="2">41.66, a</td><td>43.58, a</td><td>44.14, a</td></tr>
<tr><td>110</td><td>40.72, a</td><td colspan="2">39.43, a</td><td>40.64, a</td><td>40.26, a</td></tr>
</table>

Table 4-12 shows the effect of ripping depths (C, D1 and D2) and urea fertiliser rates (0 kg N/ha and 110 kg N/ha) with their overlapping on wheat HI. From the table, Appendix F.8 and its subdivisions, it appears that increasing both ripping depth from 0 cm to 30 cm and then to 60 cm, and N application from 0 kg/ha to 110 kg/ha as well as the overlapping between them, did not have any significant difference on the values of the HI.

- **Evanslea site**

Sorghum harvest index

Figure 4-9 shows the effect of ripping depths (C, D1 and D2) on the sorghum HI. The results of the statistical analysis for the 5% probability level on the figure’s column tops indicated that there were no significant differences between the HI values when the ripping depth increased from zero to 30 cm and then to 60 cm, respectively.

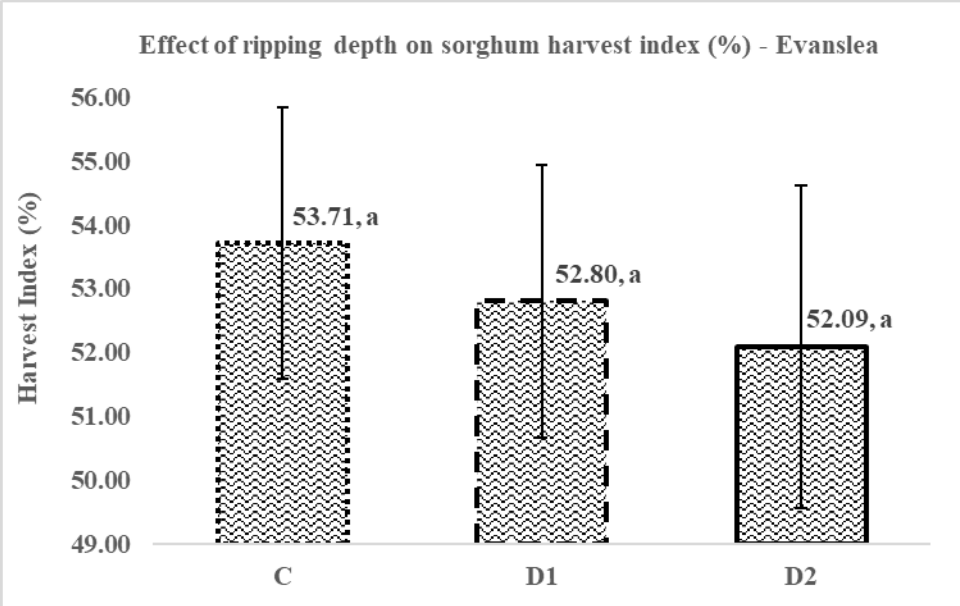

Figure 4-9: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) on sorghum harvest index (%), Evanslea site

Discussion

From the above, the HI was not successful in deep ripping or fertilisation operation assessing. Although all the differences were not significant, it was a confusing and inexplicable characteristic. Through the presented results in the two tables and the figure, it is clear that the ratio of HI for control and unfertilised soil was higher than the ripped and fertilised soils' HI. These results are in line with several studies, e.g. Barley and Naidu (1964), Storrier (1965), Fischer and Kohn (1966), Fischer (1979), Delroy and Bowden (1986) and Buah and Mwinkaara (2009).

4.1.3 Machinery unit performance parameters

4.1.3.1 Required draft force

- **Ag plot site**

The tractors and ripper used at this site were mentioned in detail in Sections 3.1.4 and 3.1.5 and illustrated in Figures 3-5 and 3-7. Figure 4-10 shows the effect of 0-30 cm and 0-60 cm ripping depths on the net draft force of the Barrow single tine ripper. From the figure, the significant difference in draft force values associated with ripping depth change can be observed clearly. The force required to pull the single tine increased from 8.59 kN to 41.7 kN (+385%), with the increased depth of shank penetration from 0-30 cm to 0-60 cm, respectively.

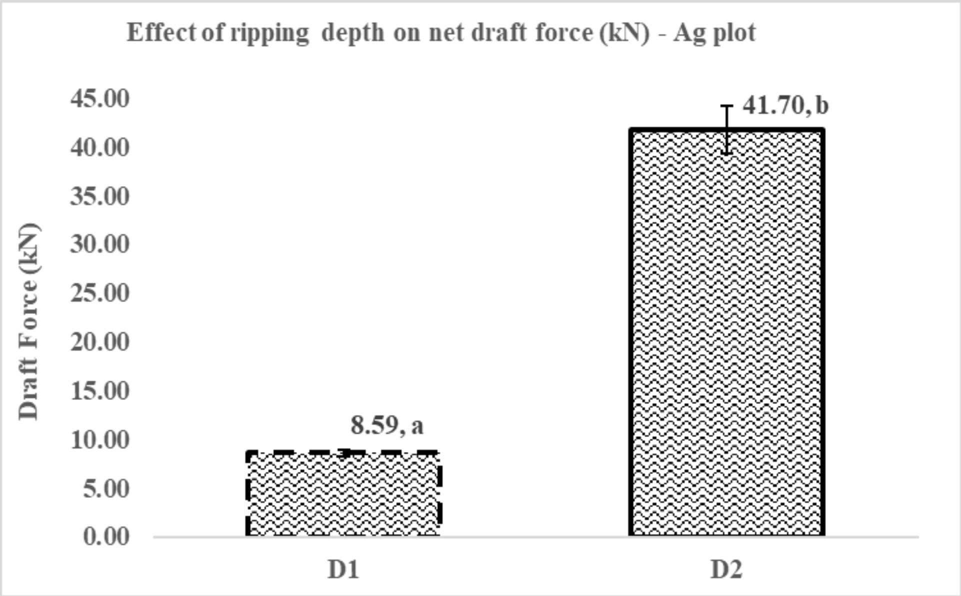

Figure 4-10: Effect of ripping depths (D1=0-30 cm) and (D2=0-60 cm) on the net force of pulling Barrow single tine ripper, Ag plot site

- **Evanslea site**

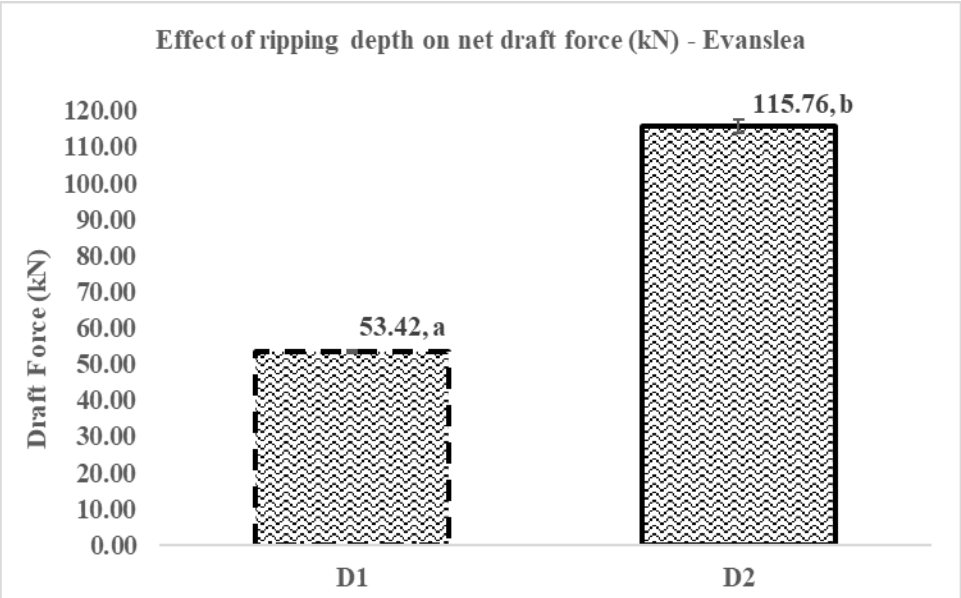

Figure 4-11: Effect of ripping depths (D1=0-30 cm) and (D2=0-60 cm) on the net force of pulling Tilco eight tines ripper, Evanslea site

The tractors and ripper used at this site were mentioned in detail in Sections 3.1.4 and 3.1.5 and illustrated in Figures 3-6 and 3-8. Figure 4-11 shows the effect of 0-30 cm and 0-60 cm ripping depths on the net draft force of the Tilco eight tines ripper. Pulling the eight tines ripper to rip the soil at a depth of 0-30 cm required a draft force of 53.42

kN while the required force for pulling increased to 115.76 kN when the ripping depth increased to 60 cm with an increased rate of 117%.

Discussion

Most researchers agree that deep tillage is an agricultural practice that require higher pulling forces, as it aims to facilitate root and water movement in or below the root growth zone. However, this force may double if the ripper moves from sandy to clay soil, and this may explain the high values for the subsoiler pull force in the soil of both fields. Also, the increasing draught force when both rippers switched to the second depth (60 cm) may be due to: 1) increasing depth meaning increasing forward soil rupture distance and disturbed volume in front of the tine, increasing draught force requirements and 2) soil layer strength and resistance to shearing in most cases increases with increasing depth because of increased particles adjacency, and therefore the soil resistance against the ripper movement will increase with increasing tine penetration.

4.1.3.2 Power requirements

- **Ag plot site**

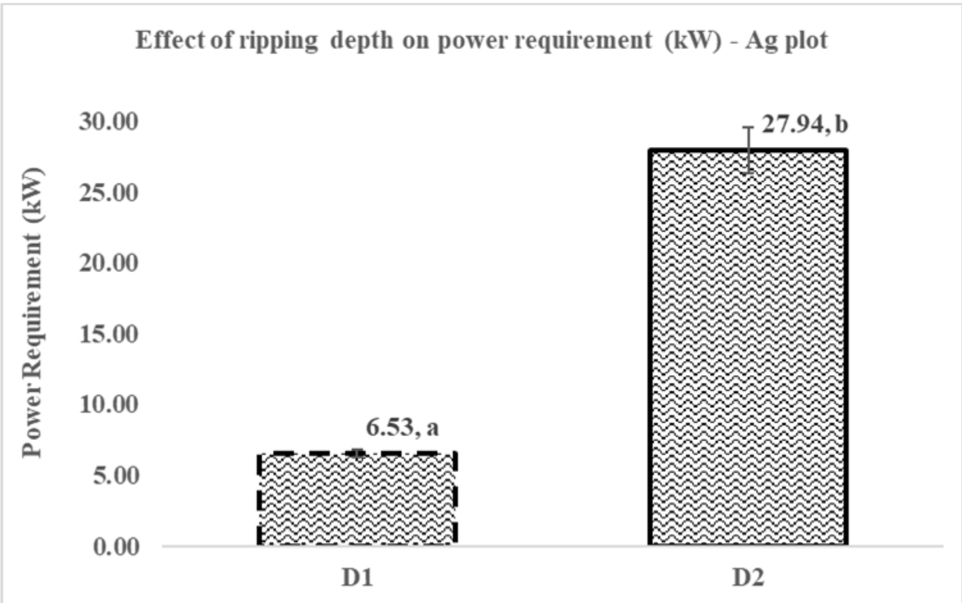

Figure 4-12: Effect of ripping depths (D1=0-30 cm) and (D2=0-60 cm) on John Deere 6150 M tractor power requirements when pulling Barrow single tine ripper, Ag plot site

Figure 4-12 shows the effect of 0-30 cm and 0-60 cm ripping depths on John Deere 6150 M power requirements when pulling a Barrow single tine ripper. From the figure, it appears that the John Deere tractor consumed 6.53 kW (8.76 hp) of its net engine power 111.9 kW (150.06 hp) to pull the barrow single tine ripper to a working depth of 30 cm while the depth of 60 cm required 27.94 kW (37.47 hp) (+328%) of engine energy for ripper movement through the soil. This is obviously a significant increase according to the statistical analysis results at $p < 0.05$.

- **Evanslea site**

Figure 4-13 shows the effect of 0-30 cm and 0-60 cm ripping depths on the John Deere 7920 power requirement to pull the Tilco eight tines ripper. It is very clear from the figure that 39.53 kW (53.01 hp) out of 108.9 kW (146.04 hp) (John Deere 7920 net engine power on drawbar points) was consumed to pull the ripper at the ripping depth of 30 cm while the required pull energy increased significantly to 83.96 kW (112.59 hp) (+112%) when the working depth increased to 60 cm.

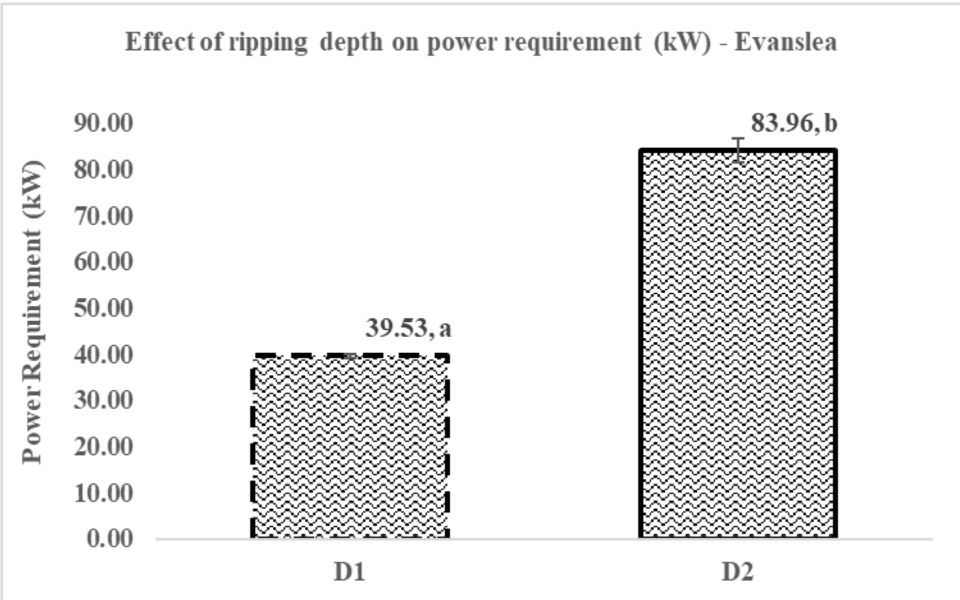

Figure 4-13: Effect of ripping depths (D1=0-30 cm) and (D2=0-60 cm) on John Deere 7920 tractor power requirements when pulling Tilco eight tines ripper, Evanslea site

Discussion

According to Equation 3-8, tractor power requirements for pulling any plough or equipment has a linear positive (upward) correlation with the horizontal (draught or pulling) force and the operational speed. As the speed factor during this study was unchanged, increasing tractor power requirements may be to the increasing horizontal force against the soil shear strength which in turn had a positive linear relationship with the depth of ripping.

4.1.4 Economic parameters

4.1.4.1 Ripping operation cost

Appendix B.1.1 shows the estimation of the total costs of owning and operating the tractors and rippers used during this study at the two sites. These results represent the deep tillage operation costs, assuming they were carried out with farm machinery. Appendix B.1.1 includes the estimated operational costs per hour and hectare. The unit of Australian dollars per hectare (AUD/ha) was adopted when discussing the statistical analysis results as it is the common unit for tillage equipment costs. Note that operational cost has been calculated annually and hourly.

- **Ag plot site**

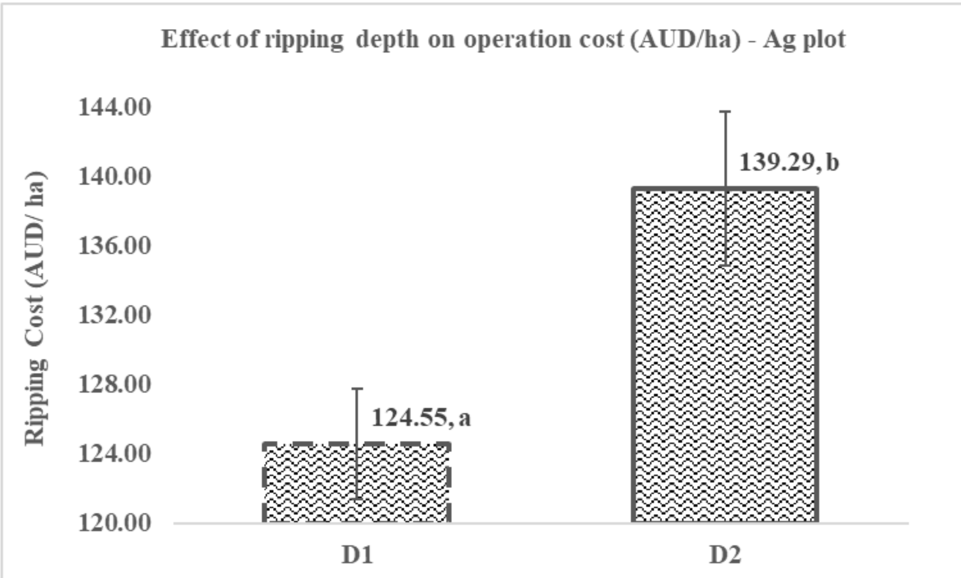

Figure 4-14: Effect of ripping depths (D1=0-30 cm) and (D2=0-60 cm) on the total machinery unit cost (John Deere 6150 M tractor + Barrow single tine ripper), Ag plot site

Figure 4-14 shows the total costs of the owning and operating John Deere 6150 M tractor with Barrow single tine ripper at two ripping operational depths in this site. The figure shows that increasing the ripping depth by lowering the 6150M John Deere's three-point linkage hydraulically from 0-30 cm then to 60 cm resulted in a significant increase in operational costs; from AUD124.55/ha to AUD139.29/ha (+12%).

- **Evanslea site**

Figure 4-15 shows the total costs of the owning and operating the John Deere 7920 tractor with Tilco eight tines ripper at the two ripping operation depths at the Evanslea site. The figure shows that increasing ripping depth by lowering the 7920 John Deere's three-point linkage hydraulically from 0-30 then to 60 cm led to an increased operational cost from AUD25.77/ha to AUD30.79/ha, respectively with an average increase of 19%.

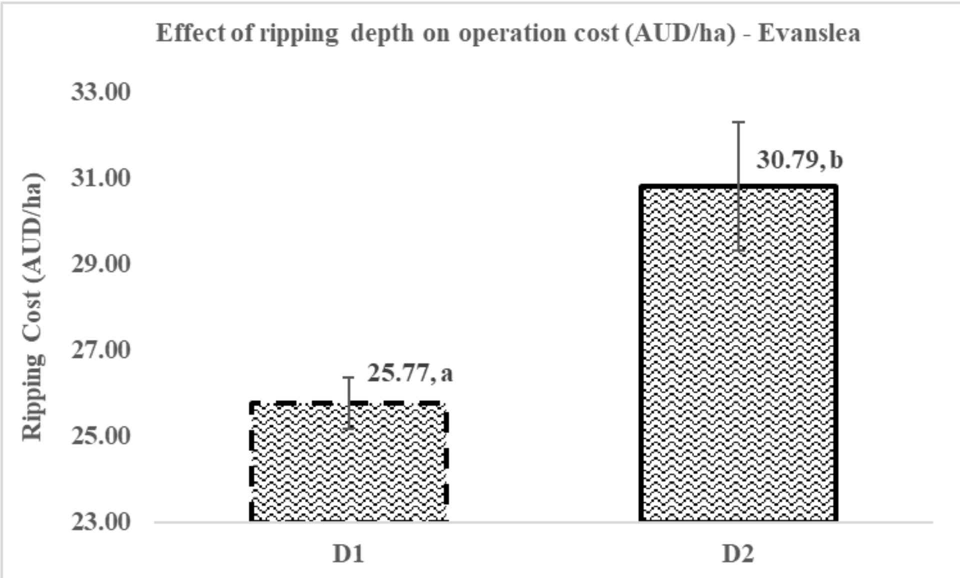

Figure 4-15: Effect of ripping depths (D1=0-30 cm) and (D2=0-60 cm) on the total machinery unit cost (John Deere 7920 tractor + Tilco eight tines ripper), Evanslea site

Discussion

The total operation costs at the two sites increased once the ripper penetration increased. Globally, the rise in oil prices has led to an increase in fuel prices. Consequently, the most influential factor on agricultural operational costs is the amount of fuel consumed. Increasing the ripping depth from 30 cm to 60 cm increased the force required to pull the subsoiler through the soil, which in turn required the tractor engine power requirements to increase to overcome soil resistance, and accordingly increased the engine crankshaft' rotational number per minute (rpm) to increase the number of four-stroke engine and this means increased fuel consumption. Also, increasing the operating depth means increasing the machinery unit (tractor + ripper) operating hours to rip one hectare, and this means an increase in the operator's wages, oil and lubricant expenditure, maintenance and repairs, as well as the replacement of worn parts, etc.

4.1.4.2 Ripping operation benefits

The deep ripping gross benefit (gross income or yield gains) and net benefit (gross margin) were calculated for both locations.

- **Gross benefit**

Ag plot site

Adding N fertiliser as urea at two rates, 0 kg/ha and 140 kg/ha after sorghum planting, and 0 kg/ha and 110 kg /ha after wheat planting has been studied as a second variable in addition to the deep ripping effect at this site. Appendix B.2.1 provides detailed information of gross income calculated for the sorghum, wheat seasons and total 2017 season at the Ag plot site.

- ***Sorghum gross benefit (gross income)***

Table 4-13: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 140 kg N/ha) with their overlap on sorghum gross benefit (AUD/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)		Av. Ripping depth (cm)
	0	140	
No ripping	1156.4, a	1238.6, a	1197.5, a
0-30	1291.4, a	1401.0, b	1346.2, b
0-60	1331.2, a	1512.9, b	1422.0, c

Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	1156.4, a	1291.4, b	1331.2, b	1259.7, a
140	1238.6, a	1401.0, b	1512.9, c	1384.2, b

Table 4-13 shows the effect of ripping depths (C, D1, and D2) and N fertiliser rates (0 kg/ha and 140 kg/ha) and their overlap on sorghum gross income. The statistical analysis shows that deep ripping had a significant effect on sorghum yield gains, as the average gross benefit increased significantly from AUD1197.5/ha to

AUD1346.2/ha (+12%) and then AUD1422/ha (+19%) when the ripping depth increased from 0 to 30 then to 60 cm, respectively.

From the Table 4-13, Appendix F.4 and its subdivisions, the fertiliser was also significant in raising the sorghum yield gains, as adding 140 kg N/ha achieved a gross income of AUD1384.2/ha with an increase of 10% compared to unfertilised treatment which had a gross income rate of AUD1259.7/ha.

The interaction between deep ripping depths and fertilisation rates had a significant effect on sorghum gross benefit. However, applying N fertiliser at 0 kg/ha and 140 kg/ha on unripped soils, did not have any significant effect on sorghum gross income. The overlap between the 0-60 cm ripping depth and N rate of 140 kg/ha was superior in getting the highest gross income from sorghum (AUD1512.9/ha), while the interaction of no ripping with no fertiliser produced the smallest sorghum gross income (AUD1156.4/ha).

- ***Wheat gross benefit (gross income)***

Table 4-14: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 110 kg N/ha) with their overlap on wheat gross benefit (AUD/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)			Av. Ripping depth (cm)
	0		110	
No ripping	422.7, a		479.0, a	450.9, a
0-30	472.4, a		554.2, b	513.3, b
0-60	545.7, a		633.7, b	589.7, c
Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	422.7, a	472.4, a	545.7, b	480.3, a
110	479.0, a	554.2, b	633.7, c	555.6, b

Table 4-14 shows the effect of ripping depths (C, D1 and D2) and N fertiliser rates (0 kg/ha and 110 kg/ha) with their interaction on wheat yield gains. From the Table 4-14 with Appendix F.9 and its subdivisions, it appears that increasing the single-tine ripper depth had a significant effect on average wheat yield gains. When the depth changed from 0 cm to 30 cm then to 60 cm, wheat yield profit increased from AUD450.9/ha to AUD513.3/ha (+14) and then to AUD589.7/ha (+31), respectively.

From the same table, it is clear that the two N rates had a significant effect on wheat gross benefit where it increased from AUD 480.3/ha to AUD555.6/ha with an increase rate of 16% when the N dose changed from 0 kg/ha to 110 kg/ha, respectively.

As for the interaction between C, D1 and D2 and the N weight in kg per hectare, the table showed that applying N rates (0 kg/ha and 110 kg/ha) on control (no ripping) plots, did not have any significant effect on the wheat gross income. While, applying N rates (0 kg/ha and 110 kg/ha) on ripped plots, have a significant effect on the wheat gross income. The highest gains in wheat grain yield were AUD633.7/ha, which resulted from an overlapping of the D2 ripping system with the N rate of 110 kg/ha, whereas the lowest gains in wheat yield which were AUD422.7/ha, resulting from the zero ripping system with zero N fertiliser application.

- ***The 2017 agricultural season's gross benefit (gross income)***

Table 4-15: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (with and without urea) with their overlap on 2017 agricultural season's gross benefit (AUD/ha), Ag plot site

<table>
<tr><td rowspan="2">Ripping Depth (cm)</td><td colspan="3">Fertiliser Rate (kg N/ha)</td><td rowspan="2">Av. Ripping depth (cm)</td></tr>
<tr><td colspan="2">Without Urea</td><td>With Urea</td></tr>
<tr><td>No ripping</td><td colspan="2">1579.1, a</td><td>1717.7, b</td><td>1648.4, a</td></tr>
<tr><td>0-30</td><td colspan="2">1763.8, a</td><td>1955.2, b</td><td>1859.5, b</td></tr>
<tr><td>0-60</td><td colspan="2">1876.8, a</td><td>2146.6, b</td><td>2011.7, c</td></tr>
<tr><td rowspan="2">Fertiliser Rate (kg N/ha)</td><td colspan="3">Ripping Depth (cm)</td><td rowspan="2">Av. Fertiliser rate (kg N/ha)</td></tr>
<tr><td>No ripping</td><td>0-30</td><td>0-60</td></tr>
<tr><td>Without Urea</td><td>1579.1, a</td><td>1763.8, b</td><td>1876.8, b</td><td>1739.9, a</td></tr>
<tr><td>With Urea</td><td>1717.7, a</td><td>1955.2, b</td><td>2146.6, c</td><td>1939.8, b</td></tr>
</table>

Table 4-15 with Appendix F.11 and subdivisions show the effect of ripping depths (C, D1 and D2) and urea application options (with and without) and their overlap on the 2017 agricultural season's gross benefit at the Ag plot site. The tabled data shows that deep ripping had a significant effect on the 2017 season's gross benefit as the benefit increased significantly from AUD1648.4/ha to AUD1859.5/ha (+13%) and then

AUD2011.7/ha (+22%) when the subsoiling depth increased from 0 cm to 30 cm then to 60 cm, respectively.

Furthermore, it can be observed that adding urea to the soil after sorghum and wheat planting increased the total profit of season 2017 from AUD1739.9/ha to AUD1939.8/ha with a rate increase of 11%.

As for the interaction between deep ripping depths and urea addition options, the table shows that the C, D1 and D2 ripping systems increased the 2017 season gross income significantly of plots under urea addition option. Also, the urea application on C, D1 and D2 plots increased the 2017 season gross income significantly. In sum, the interaction between the 0-60 cm deep ripping and urea application achieved the highest 2017 gross income season (AUD2146.6/ha) while the interaction between zero ripping and no urea fertiliser application produced the lowest gross income for the 2017 growing season (AUD1579.1/ha).

Evanslea site

At this site, after deep tillage, all plots were subjected to the farmer's practices. Appendix B.2.2 shows the detailed information of gross income, total variable cost and gross margin for the 2018 sorghum seasons at the Evanslea site.

- ***Sorghum gross benefit (gross income)***

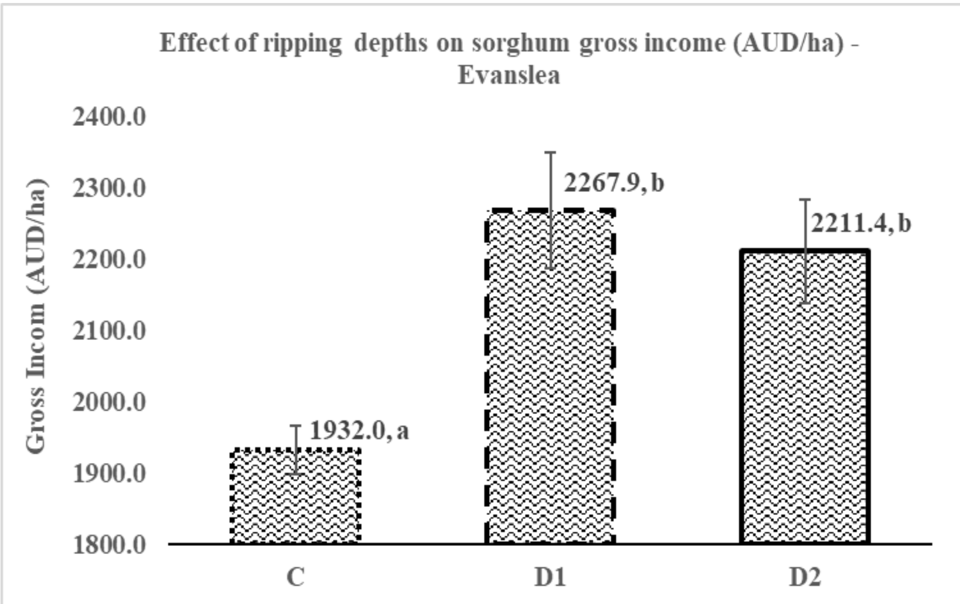

Figure 4-16: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) on sorghum gross income (AUD/ha), Evanslea site

Figure 4-16 shows the effect of ripping depths (C, D1 and D2) on sorghum yield gains. Through the figure, it can be concluded that the D1 and D2 ripping systems had a significant effect on increasing sorghum gross income. In comparison with the zero ripping soil's gross income which was AUD1932/ha, the 0-30 cm ripping achieved a gross income of AUD2267.9/ha with a rate increase of 17%, while the 0-60 cm ripping achieved a gross income of AUD2211.4/ha with a 14% increase. The D1 plots' average gross income was more than the D2 plots' income however, the difference between the two treatment outcomes was not significant.

Discussion

It is quite clear that both deep ripping depths were effective in raising the gross income of the planted crops after at both locations. This can be explained by referring to Equation 3.19, which shows that both the selling price (P_C) and the yield (Y_{MO}) have a positive effect on the gross income value (GI). Given that the selling price is constant, when applying this equation at the end of each crop's harvesting, the quantity of the crop product is the influencing factor. As deep tillage raised the cereal crops' productivity for reasons previously explained, the total profit of crops (individually or collectively) has a strong correlation with deep tillage application.

Increased ripper' tine penetration at the Ag plot site led to an increase in the gross income of its crops, but the shallow ripper depth was the most profitable at the Evanslea site. This may also be attributed to the direct linkage of gross income to product quantity, which increased at the Ag plot and decreased at Evanslea when the ripper operation depth changed from 30 cm to 60 cm (D1 to D2). This may be due to the machinery traffic farming system, which was random at the Ag plot field and control at Evanslea, thus the Ag plot's soil bulk density was much higher than the Evanslea soil bulk density, also taking into account that the two soils are different in clay percentage and type. Deep tillage, as we mentioned earlier, reduced soil bulk density and soil strength within the boundary of ripping depth. As a result, D2 produces more fragmented soil and may led to deeper placement of seeds than the sowing required depth at CTF, thus the emergence seedling percentage will decrease. This may reduce the plant population and thus productivity. In addition, D2 soil's water may drain away from the young plants' roots, unlike the D1 plants, where water may be available within the root growth zone.

As for fertilisation rates, the gross profit significantly increased when using the N fertiliser. This may be due to the increasing crop yield when applying fertiliser for reasons that have been mentioned in detail previously. Accordingly, gross profit increased because of the direct and positive correlation to the crop productivity.

- **Net benefit**

Ag plot site

The sorghum, wheat and total 2017 season's net benefit under three deep ripping systems and two N fertiliser rates with their overlaps were studied. How to obtain the net profit values from planting the above crops is detailed in Appendix B.2.1.

- ***Sorghum net benefit (gross margin)***

Table 4-16: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 140 kg N/ha) with their overlaps on sorghum net benefit (AUD/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)			Av. Ripping depth (cm)
	0		140	
No ripping	1039.1, a		1035.3, a	1037.2, a
0-30	1049.5, a		1073.1, a	1061.3, a b
0-60	1074.5, a		1170.3, a	1122.4, b
Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	1039.1, a	1049.5, a	1074.5, a	1054.3, a
140	1035.3, a	1073.1, a b	1170.3, b	1092.9, a

Table 4-16 shows the effect of ripping depths (C, D1 and D2) and N fertiliser rates (0 kg/ha and 140 kg/ha) with their overlaps on sorghum gross margin. Regarding tillage systems, from the Table 4-16, Appendix F.5 and its subdivisions, it appears that shifting from zero ripping to D1, and from D1 to D2, increased sorghum net benefit from AUD1037.2/ha to AUD1061.3/ha and from AUD1061.3/ha to AUD1122.4/ha. However, these increases were not significant. Shifting from zero ripping to the D2 system led to a significant increase in the sorghum net benefit from AUD1037.2/ha to AUD1122.4/ha, respectively with an increase rate of 8%.

With regards to the N fertiliser rates, the table and appendices both show that shifting from 0 kg N/ha to 140 kg N/ha rate did not achieve any significant difference in the sorghum gross margin, although the shift did increase the net benefit of sorghum from AUD1054.3/ha to AUD1092.9/ha, respectively.

As for the interaction between deep tillage systems and N rates, the table and appendices show that all interactions had no significant effect on sorghum gross margin, except for the interaction of 140 kg N/ha rate with the D2 ripping system which was significant and produced the highest gross margin of sorghum (AUD1170.3/ha). Additionally, the overlapping of zero ripping with N application of 140 kg/ha produced the lowest sorghum gross margin which was AUD1035.3/ha.

- ***Wheat net benefit (gross margin)***

Table 4-17: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (0 kg N/ha and 110 kg N/ha) with their overlaps on wheat gross margin (AUD/ha), Ag plot site

Ripping Depth (cm)	Fertiliser Rate (kg N/ha)			Av. Ripping depth (cm)
	0		110	
No ripping	349.2, a		337.7, a	343.5, a
0-30	398.9, a		412.9, a	405.9, b
0-60	472.2, a		492.4, a	482.3, c
Fertiliser Rate (kg N/ha)	Ripping Depth (cm)			Av. Fertiliser rate (kg N/ha)
	No ripping	0-30	0-60	
0	349.2, a	398.9, a	472.2, b	406.8, a
110	337.7, a	412.9, b	492.4, c	414.3, a

Table 4-17 and Appendix F.10 and subdivisions show the effect of ripping systems (C, D1 and D2) and N fertiliser rates (0 kg/ha and 110 kg/ha) with their overlapping on wheat gross income (second crop). From the Table 4-17, Appendix F.10 and its subdivisions, it appears that the shift from the C system to D1 and then to D2 had increased the average wheat net benefit significantly from AUD343.5/ha to AUD405.9/ha (+18) and then to AUD482.3/ha (+40), respectively.

Also, from the same table it is clear that the change in N dose from 0 kg/ha to 110 kg/ha increased the wheat net profit from AUD406.8/ha to AUD414.3/ha (+2%), however this increase was not significant.

As for the interaction between tillage systems and N rates, the table and appendices show that the difference in wheat net benefit from the 0 kg N/ha and 110 kg N/ha rates on ripped plots was significant, except for the overlapping of 0 kg N/ha with D1 ripping (AUS398.9/ha) where the difference was insignificant compared with the overlapping of 0 kg N/ha with zero ripping (AUS349.2/ha). In short, the overlapping of the D2 ripping system with N application of 110 kg/ha achieved the highest wheat gross margin (AUD492.4/ha) while the overlapping of zero ripping with N application of 110 kg/ha produced the lowest gross margin of wheat which was AUD337.7/ha.

- ***The 2017 agricultural season's net benefit (gross margin)***

Table 4-18: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) and fertiliser rates (with and without urea) with their overlaps in agricultural season 2017 net benefit (AUD/ha), Ag plot site

<table>
<tr><td rowspan="2">Ripping Depth (cm)</td><td colspan="3">Fertiliser Rate (kg N/ha)</td><td rowspan="2">Av. Ripping depth (cm)</td></tr>
<tr><td colspan="2">Without Urea</td><td>With Urea</td></tr>
<tr><td>No ripping</td><td colspan="2">1388.3, a</td><td>1373.0, a</td><td>1380.7, a</td></tr>
<tr><td>0-30</td><td colspan="2">1448.4, a</td><td>1486.0, a</td><td>1467.2, a</td></tr>
<tr><td>0-60</td><td colspan="2">1546.7, a</td><td>1662.7, a</td><td>1604.7, b</td></tr>
<tr><td rowspan="2">Fertiliser Rate (kg N/ha)</td><td colspan="3">Ripping Depth (cm)</td><td rowspan="2">Av. Fertiliser rate (kg N/ha)</td></tr>
<tr><td>No ripping</td><td>0-30</td><td>0-60</td></tr>
<tr><td>Without Urea</td><td>1388.3, a</td><td>1448.4, a b</td><td>1546.7, b</td><td>1461.1, a</td></tr>
<tr><td>With Urea</td><td>1373.0, a</td><td>1486.0, a</td><td>1662.7, b</td><td>1507.2, a</td></tr>
</table>

Table 4-18 shows the effect of ripping depths (C, D1 and D2) and urea application options (with and without) with their overlaps on the 2017 agricultural season's gross margin at the Ag plot site. The tabled data shows, that shifting from zero ripping to D2 and from D1 to D2, increased the Ag plot's 2017 season's gross margin significantly from AUD1380.7/ha to AUD1604.7/ha (+16%) and from AUD1467.2/ha to AUD1604.7/ha (+9%), respectively. Shifting from zero ripping to D1, also increase the gross margin of the 2017 Ag plot season 2017 from AUD1380.7/ha to AUD1467.2/ha (+6%), but this increase was not significant.

From the Table 4-18, Appendix F.12 and its subdivisions, it can also be observed that adding urea to the Ag plot after the emergence of sorghum and wheat seedlings increased the net profit of 2017 season from AUD1461.1/ha to AUD1507.2/ha (+3%), however this increase was not significant.

As for the interaction between deep ripping depths and urea addition options, the table shows that the 2017 net benefit of overlapping of the two urea options with C, D1 and D2 ripping systems was not significant. However, the overlapping of adding and not adding urea options with D2 plots had a significant effect on the 2017 gross benefit. In sum, the interaction between 0-60 cm deep ripping and urea application decision was superior in getting the highest 2017 gross margin season (AUD1662.7/ha) while the interaction between zero ripping and adding urea option resulted in the lowest gross margin of the Ag plot 2017 season (AUD1373/ha).

Evanslea site

Appendix B.2.2 contains detailed information of yield, selling price, and total costs for the sorghum crop at for 2018, and shows how to estimate the net profit of sorghum cultivation under the three tillage systems.

- ***Sorghum net benefit (gross margin)***

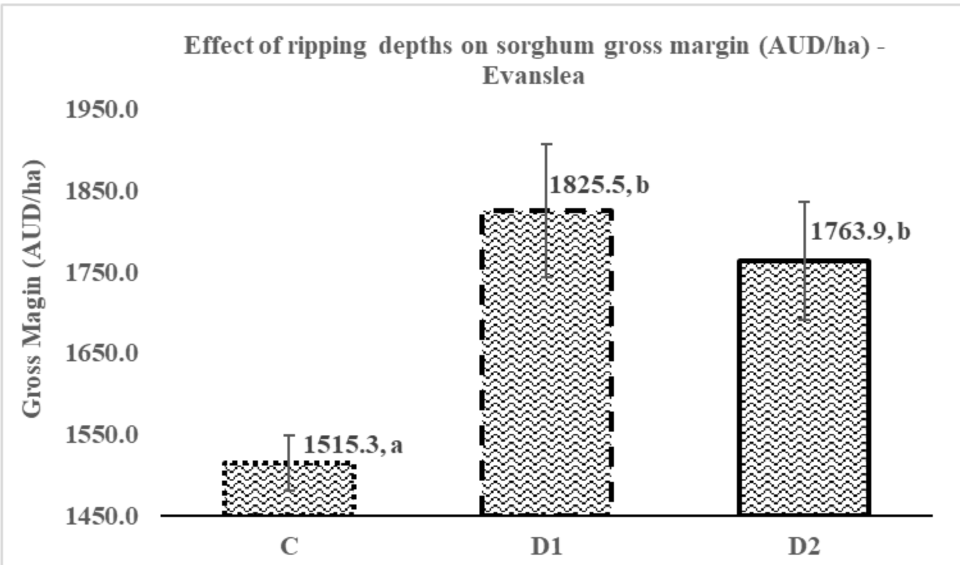

Figure 4-17: Effect of ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) on sorghum gross margin (AUD/ha), Evanslea site

Figure 4-17 shows the effect of ripping depths (C, D1 and D2) on the sorghum gross margin. It can be seen from the figure that the D1 and D2 both had a significant effect on the sorghum net benefit. Clearly, shifting from zero ripping to D1 and then to D2, increased the gross margin of sorghum significantly from AUD1515.3/ha to AUD1825.5/ha (+20%) and then to AUD1763.9/ha (+16%), respectively. Returning to the table again, it can also be observed that the average net benefits of D1 plots was just a little higher than the D2 plots' net benefits, yet the difference between the two systems' benefits was not significant.

Discussion

When reviewing the tables and figure for the gross margin (net profit) results for the Ag plot and Evanslea sites, the following conclusions could be made:-

At the Ag plot site, after sorghum harvest (the first crop after deep ripping conducting), D2 ripping was the only system that made a significant difference in net benefit compared to net benefit of the zero ripping system. The D1 system at this stage did not have any significant effect.

After wheat harvesting, the next crop after applying ripping systems, D1 and D2 both had a significant effect on the net benefit values compared to the control soil's net benefits. Also, the benefit increased with the increasing ripping depth. This is due to the fact that the accrued benefit from D1 at the end of the first crop season covered the total variable costs (TVC), and what remained did not make a significant difference compared to the Control's net benefit, while the D2 system's benefit covered the total costs and what remained was significant to the Control's net benefit. As for wheat/next season, earnings from both the D1 and D2 systems had a significant effect compared to the Control soil's net profit, since the costs of deep ripping for this season were considered zero, and this is consistent with what Reeder et al. (1993) and Chamen (2015) mentioned; that the real benefit of deep tillage can be achieved during the next crop through an increase in its yield.

With regards to the 2017 season's gross margin at the Ag plot site, it seems that the D2 system achieved a significant difference in gross margin compared to the D1 and zero ripping systems. The reason is that the D2 benefit covered the two crops' growing costs in addition to its application cost. The D1 system was unable to achieve a significant difference after paying the costs of planting the two crops and ripping.

The application of N fertiliser at the Ag plot site increased the grain productivity of both sorghum and wheat significantly however, the achieved gross margin from these increases was not significant when compared to the non-fertilised soil's gross margin for the two growing seasons in addition to the 2017 agricultural season. The reason may mainly be attributed to the steady rise in the global price of N fertiliser. Application of the optimal N fertiliser achieved an increase of sorghum grain yield by up to 440 kg/ha and about 290 kg/ha for wheat. The achieved gross income from these increases covered the costs of fertiliser purchases and the application process. Thus, the remaining benefit (gross margin) was not significant when compared with the of non-fertiliser plots' gross margin.

At the Evanslea site, the average of the obtained gross margin from sorghum cultivation after D1 and D2, had a significant effect when compared to zero ripping net benefit. This is mainly due to the low costs of deep tillage and to the high yield on this site. The cost of D1 and D2 were AUD25.77/ha and AUD30.79/ha, respectively at this site. The cost reduction is due to the large operating width of the ripper which consists of eight tines that produced more ripped hectares during the time unit compared to the single-tine ripper that used at the Ag plot site. So, more time was needed to rip one hectare, which in turn increased ripping costs from AUD124.55 to AUD139. 29/ha when switching from D1 to D2. Sowing row spacing of 0.75 m where the tractors and self-propelled equipment entry system is controlled, compared with row spacing of 0.9 m on farm under the random traffic farming system may be the reason for Evanslea's high yield. Moreover, since the gross margin is a result of the difference between gross income and total variable cost (Equation 3-20), the D1 at Evanslea site was first ripping system in achieving the highest net benefit followed by D2 system in this task.

4.1.5 Conclusion

Compaction is one of the key reasons for the recent decline in arable land yield around the world. Most commercial farm management policies have adopted the introduction of large and heavy equipment, machinery and tractors to meet the demand for food as a result of to the steady population growth. To a depth of almost 80 cm, the behavior of two different clayey soils under two different traffic farming systems after loosening with two types of rippers were monitored during this study. These investigations were accompanied by calculations of some machinery unit technical performance indicators, costs, yield components, and profits. The importance of this section lies in the scarcity of such studies dealing with deep tillage, especially in the high clay content soils due to the high draught force and power requirements of the tine/s and tractor respectively, making it an expensive practice in conclusion of the most studies, research and reports.

In spite of the fact that it consumes a lot of fuel, power and money (Kichler, Fulton, Raper, McDonald, & Zech, 2011; Lacey et al., 2001; McLaughlin et al., 2006; Patterson et al., 1980), according to many studies e.g. Ellington (1986), Al-Adawi and Reeder (1996), Renton and Flower (2015), Kuhwald et al. (2017) and Scanlan and Davies (2019), deep tillage alleviates soil compaction and maintains crop production by improving soil aeration and drainage, reducing soil strength and waterlogging, increasing soil fertility and enhancing soil structure when attaching an organic or chemical injector behind the ripper tine. This study may comply with many researchers recommendations such as Chen et al. (2005), Chamen et al. (2015); and Manik et al. (2019), on the necessity of conducting accurate and long investigations regarding the impact of deep tillage on the properties of clayey soil and their crops, as well as farm profitability. The conclusion of this study can be summarized by a set of points for each site as follows:

At Red Ferrosol soil - Ag plot site

- D2 (0-60 cm) was superior in ameliorating soil properties as it achieved the lowest significant value of the dry bulk density (1.34 g/cm^3), CI (2972 kPa), and the highest insignificant percentage of water content (27.28%) compared to no ripping (compacted soil) and D1 (0-30 cm) system
- The 0-60 cm ripping system (D2) achieved the highest yield increases of sorghum grain (5038 kg/ha), sorghum dry biomass (12494 kg/ha), wheat grain (2251 kg/ha), and wheat biomass (5373 kg/ha) compared to D1 (0-30 cm) and zero ripping
- The addition of N fertiliser achieved the highest significant yield increases of sorghum grain (4904 kg/ha), sorghum dry biomass (12297 kg/ha), wheat grain

(2121 kg/ha), and wheat biomass (5278 kg/ha) compared to no urea fertiliser application treatment yields

- The interaction between the D2 and adding N fertiliser obtained the highest significant values of sorghum grain (5360 kg/ha), sorghum dry biomass (13269 kg/ha), wheat grain (2419 kg/ha), and wheat biomass (5960 kg/ha)
- The Barrow single tine ripper under D1 (0-30 cm) was significantly superior, giving the lowest net draft force (8.59 kN) and tractor power (6.53 kW) compared to D2 (0-60 cm)
- Economically, D1 was superior with the lowest operational cost (AUD124.55/ha) which was also significant compared to the cost operation of D2 (AUD139.29/ha)
- The D2 ripping system achieved the highest significant value of sorghum gross benefit (AUD1422/ha), sorghum net benefit (AUD1122.4/ha), wheat gross benefit (AUD589.7/ha), wheat net benefit (AUD482.3/ha), 2017 season gross benefit (AUD2011.7/ha), and 2017 season net benefit (AUD1604.7/ha) compared to D1 and zero ripping systems
- Applying N fertiliser was economically superior in achieving the highest significant value of sorghum gross benefit (AUD1384.2/ha), wheat gross benefit (AUD555.6/ha) and the 2017 season gross benefit (AUD1939.8/ha) compared to no N fertiliser application treatment
- The interaction between D2 ripping and N fertiliser application was economically superior in achieving the highest significant value of sorghum gross benefit (AUD1512.9/ha), sorghum net benefit (AUD1170.3/ha), wheat gross benefit (AUD633.7/ha), wheat net benefit (AUD492.4/ha), 2017 season gross benefit (AUD2146.6/ha), and 2017 season net benefit (AUD1662.7/ha) compared to other interactions
- The HI was not useful in assessing either deep tillage or fertilisation operations on crop performance.

At Black Vertosol soil - Evanslea site

- The D2 ripping system was superior in ameliorating soil properties, as it achieved the lowest significant value of the dry bulk density (1.02 g/cm^3), CI

(1012 kPa), and the highest percentage of water content (50.94%) compared to zero ripping (compacted soil) and the D1 systems

- The D1 ripping system achieved the highest significant yield increases of sorghum grain (8100 kg/ha) and dry biomass (15369 kg/ha) compared to zero ripping (C). These increases were not significant for D2 soil productivity of sorghum grain and biomass
- The Tilco eight tines ripper under the 0-30 cm of ripping (D1) was significantly superior in that it required the lowest net draught force (53.42 kN) and tractor power (39.53 kW) compared to D2 (0-60 cm) system
- Economically, the 0-30 ripping (D1) had the lowest operation costs (AUD25.77/ha) which was also significant compared to the cost of 0-60 ripping (D2) (AUD30.79/ha)
- The 0-30 cm ripping system (D1) achieved the highest significant value of sorghum gross benefit (AUD2267.9/ha) and net benefit (AUD1825.5/ha) compared to the zero ripping, however these benefits were found not significant with the financial incomes of the 0-60 deep ripping system (D2)
- The HI at this site also was not an effective guide for assessing the efficiency of deep ripping impact on the treated soils' productivity.

It is hoped that this study will support the management of Queensland farms, and Australian farms more generally in formulating effective decisions that confront the risks facing the agricultural sector. However, this is not enough as the current stage requires intensifying efforts to conduct further investigations and field studies that address the issue of soil compaction and how to alleviate its negative effects on clay soils, such as black and grey Vertosols soils. These soils are fertile, have interesting properties, and occupy large areas that are devoted to important crops such as cotton and cereals. Clay soil easily compacted under continued cropping and frequent traffic of machinery and tractors or heavy equipment in inappropriate soil conditions. How to overcome this problem had occupied several researchers' attention. Mixing Vertosols with gypsum, lime, organic and chemical fertilisers, as well as amendment are the most common strategies, but they have not been largely used with the deep tilling.

Controlled traffic farming (CTF) is a strategy intended to confine compaction to permanent traffic lanes zones (McHugh et al., 2009; Tullberg et al., 2007). However, it seems that the axle load pressure of farm machinery may not remain trapped inside these areas. At Evanslea, after collecting soil bulk density samples and recording penetrometer readings, it was observed that the average bulk density and strength of the soils close to both sides of permanent traffic lanes were 5% and 8% higher than the bulk density and strength of the distant soils, respectively. Consequently, during the sorghum season, it is highly likely that four of the 16 planting rows were under this impact, so 2500 m^2 of the CTF hectares' soil may be exposed to this negative effect which in turn will affects crop productivity.

The combination of deep ripping with CTF may not only sustain the positive effects of deep ripping in the long-term, but also sustain stable (and perhaps higher) crop productivity. Conducting further and more long-term investigations on these soils under this system are recommend after: 1) conducting several depths of deep ripping to find out which depth is the most appropriate technically, productively and economically and 2) using modified ripper tines to penetrate very deeply near the permanent machines paths and less deeply for the rest of the field with conventional and existing rippers to find out which one has the best influence on soil, plant and costs parameters.

4.2 Investigating the Godwin and O'Dogherty single tine model's validity in two Queensland high clay content soils

This section contains the measured values of the single tine ripper's draught force under two working depths in high clay content soil at the Ag plot and Evanslea sites. It also covers the physical conditions of the two soils, as well as the tines' operational conditions when performing the above tasks, which were employed to verify the validity of the G&O single tine model for predicting the pulling force under each operational depth and their suitability for such soils.

4.2.1 Ag plot site

The experimental and laboratory model verification steps for this site are detailed in Al-Halfi et al. (2017) and in Section 3.2. Table 4-19 shows the soil conditions and textures as well as the tine's working conditions at two depths. This table also contains the measured and predicted draft force with the error rate of G&O single tine model predictions.

The dry bulk density, bulk unit weight, moisture content and the CI of the site soil profile up to 75 cm during the verification experiment are shown in Appendix E.1 and subdivisions. Appendices E.3.1 and E.3.2 show the results (predicted draught force) of the G&O single tine model after feeding with the two working tillage depths' soil and tine conditions, respectively.

Table 4-19: Single tine's operational and soil conditions during draft force tests that approved in feeding, running and predictability validating of the G&O single tine model for Red Ferrosol soil - Ag plot site

Ag plot - USQ				
Draft force (D)	Working depth (d) (m)			Unit
	0.25		0.6	
Measured draft force	8.59, a		41.70, b	kN
Predicted draft force	7.48, a		43.28, b	kN
Model error	-12.92		+3.79	%
The average of measured parameters of the tine and soil during the operation tests				
Measured Parameters	Symbol	Working depth (d) (m)		Unit
		0.25	0.6	
Tine foot (tip) width	w	0.095	0.095	m
Tine foot (tip) rake angle	α	35	35	degree
Tine operation velocity	v	0.76	0.67	m/s
Soil bulk unit weight (density)	γ	17.84	18	kN/m^3
Soil cohesion	C	32.48	33.63	kN/m^2
Soil internal friction angle	φ	36.84	36.37	degree
Soil surcharge	q	0	0	kN/m^2
Soil-metal friction angle	δ	23.2	22.32	degree
Adhesion	C_a	18.5	18.11	kN/m^2
Clay	Ć	66.25	71.88	%
Sand	S	21.88	8.12	%
Silt	M	11.87	20	%

4.2.2 Evanslea site

The experimental and laboratory model verification steps are detailed in Section 3.2. Table 4-20 shows the measured and predicted draught force with the error rate of G&O single tine model predictions. It contains the clay, sand and silt proportions and the conditions of the soil as well as the tine working conditions at two depths.

Appendix E.2 and subdivisions show soil dry bulk density, bulk unit weight, moisture content, and CI up to 75 cm during the verification experiment. While the predicted draught force via running of the G&O single tine model after feeding with the two working tillage depths' soil and tine conditions were shown in Appendices E.4.1 and E.4.2.

Table 4-20: Single tine's operational and soil conditions during draft force tests that approved in feeding, running, and predictability validating of G&O single tine model for Black Vertosol soil - Evanslea site.

<table>
<tr><td colspan="5">Evanslea site</td></tr>
<tr><td colspan="2" rowspan="2">Draft force (D)</td><td colspan="2">Working depth (d) (m)</td><td rowspan="2">Unit</td></tr>
<tr><td>0.3</td><td>0.5</td></tr>
<tr><td colspan="2">Measured draft force</td><td>18.40, a</td><td>37.00, b</td><td>kN</td></tr>
<tr><td colspan="2">Predicted draft force</td><td>19.65, a</td><td>41.41, b</td><td>kN</td></tr>
<tr><td colspan="2">Model error</td><td>+6.79</td><td>+11. 92</td><td>%</td></tr>
<tr><td colspan="5">The average of measured parameters of the tine and soil during the operation tests</td></tr>
<tr><td rowspan="2">Measured Parameters</td><td rowspan="2">Symbol</td><td colspan="2">Working depth (d) (m)</td><td rowspan="2">Unit</td></tr>
<tr><td>0.3</td><td>0.5</td></tr>
<tr><td>Tine foot (tip) width</td><td>w</td><td>0.095</td><td>0.095</td><td>m</td></tr>
<tr><td>Tine foot (tip) rake angle</td><td>α</td><td>47</td><td>45</td><td>degree</td></tr>
<tr><td>Tine operation velocity</td><td>v</td><td>0.73</td><td>0.72</td><td>m/s</td></tr>
<tr><td>Soil bulk unit weight (density)</td><td>γ</td><td>16.38</td><td>16.63</td><td>kN/m^3</td></tr>
<tr><td>Soil cohesion</td><td>C</td><td>60.51</td><td>58.29</td><td>kN/m^2</td></tr>
<tr><td>Soil internal friction angle</td><td>φ</td><td>21.35</td><td>20.53</td><td>degree</td></tr>
<tr><td>Soil surcharge</td><td>q</td><td>0</td><td>0</td><td>kN/m^2</td></tr>
<tr><td>Soil-metal friction angle</td><td>δ</td><td>17.29</td><td>16.51</td><td>degree</td></tr>
<tr><td>Adhesion</td><td>C_a</td><td>3.44</td><td>2.42</td><td>kN/m^2</td></tr>
<tr><td>Clay</td><td>Ć</td><td>64.06</td><td>66.25</td><td>%</td></tr>
<tr><td>Sand</td><td>S</td><td>12.03</td><td>11.25</td><td>%</td></tr>
<tr><td>Silt</td><td>M</td><td>23.94</td><td>22.5</td><td>%</td></tr>
</table>

Discussion

From the soil appendices, when examining the ranges' soil conditions in which the single tine was worked, especially the soil strengths of 2806 kPa and 3540 kPa, as well as 2008 kPa and 3033 kPa at the first and second working depths for both the Ag plot and Evanslea sites respectively, it can be judged that both soils were within compaction boundaries that could hinder root growth (Atwell, 1993; Busscher et al., 1987; Letey, 1958; Taylor & Gardner, 1963).

The above soil strength values may provide a clear picture of the resistance facing the plough's operating parts (the parts which are in direct contact with the soil) as it passes through these soils. So, the measured forces required to pull the ripper under both depths were somewhat high, even though the plough was classified as a single-shank-ripper. Furthermore, the ripper tine behaved as a chisel at both depths at both sites according to the proportions between the working depth and the tine width (*d*/*w*) approved by Godwin and O'Dogherty (2007), and this may be another reason for the high measured draught values.

The average of the measured internal friction angle for the Ag plot (36.60˚) and Evanslea (20.94˚) undisturbed soil depths samples were greater than Godwin and O'Dogherty guidelines for clay soils (10˚), however they were consistent with McKyes (1985) and Ahmadi (2017) results, which reached 37˚ for clay soils. Also, from the data in the two tables, the average internal friction angle of the Ag plot's soil was 43% greater than the average internal angle of the Evanslea soil, and this may be due to the percentage of sand that was higher in the Ag plot soil layers. Another reason that may support the high angle of the Ag plot soil's internal friction is the tendency of Red Ferrosol soil particles to agglomerate into aggregates due to the amounts of oxalate iron, silicon and aluminums (Bell, Moody, Yo, & Connolly, 1999; Isbell, 1994; Lacey & Wilson, 2001; Mullins & Ley, 1995; Shainberg, 1992).

Pursuant to the Godwin and O'Dogherty recommendations about measuring the soil external friction angle rather than deducing it from the internal friction angle value, and according to what M. Kirby (personal communication, March 15, 2016) suggested when calculating this angle for undisturbed soil samples, the internal friction angle values were 0.62 and 0.81 of the internal friction angle values for the Ag plot and Evanslea sites, respectively. These ratios were somewhat close to the guidelines of Godwin and O'Dogherty (0.5 to 0.7) and Mandal and Thakur (2010) (0.66), however laboratory or field calculations are necessary to ensure accuracy.

Cohesion varied between the two soils, the Ag plot's Red Ferrosol average soil cohesion (33.06 kN/m^2) was in line with the Godwin and O'Dogherty guidelines (within the thirties limits), while the average Evanslea Black Vertosol soil cohesion (59.4 kN/m^2) was 44% more coherent than the Ag plot soil. The Black Vertosol soil result were confirmed by another Black Vertosol soil test results belonging to Dio Antille PhD student, which was conducted in one of the Trilab laboratories - Geebung, QLD, 4034 (Appendix E.5 and subdivisions). The Trilab tests showed that the Black Vertosol soil had a cohesion of 65.3 kPa with 21.8˚ internal friction angle.

Furthermore, the two tables show that the adhesion value of the two soils is different, as the average was 18.31 kN/m^2 for the Ag plot while it was 2.93 kN/m^2 for Evanslea.

The high adhesion value of the Ag plot soil may have a close relationship to the nature of its mineral content, as well as to the values of internal and external friction angles that were greater than the Evanslea soil angles. However, the adhesion result of the Trilab laboratories were largely consistent with the USQ lab results for the adhesion of the Black Vertosol soil.

The average readout of the dynamometer device increased from 8.59 kN to 41.70 kN at the Ag plot site, and from 18.40 kN to 37.0 kN at Evanslea when shifting from the first to second depth. Thus, by relying on the practical speed established in Tables 4-19 and 4-20, the power required to pull the single-leg ripper increased from 6.53 kW to 27.94 kW (8.75 hp to 37.47 hp) for the Ag plot tractor, and from 13.98 kW to 24.79 kW (18.01 hp to 35.72 hp) for the Evanslea tractor. The increased requirements for single tine ripper pulling force and its tractor power when increasing tine penetration through the soil are in line with most of the previous and current studies' results.

When feeding the soil and tine parameters detailed in Table 4-19, comparison with the measured draught force at the Ag plot (8.59 kN and 41.70 kN), the model predicted the draught force with an average error of -12.92% (7.48 kN) for the first working depth (0.25 m) and with +3.79% (43.28 kN) for the second working depth (0.6 m). Similarly, at Evanslea, after feeding Table 4-20 soil and tine values and running the model, the predicted draught force was 19.65 kN and 41.41 kN with an average error of + 6.79 and +11.92% in comparison to the averaged measured draught force results (18.40 kN and 37.00 kN) under working depths of 0.3 m and 0.5 m, respectively. Generally, for both sites, the model's error rate in its predictions of the single-tine ripper draught force requirements occurred within boundaries of ±8% (Figure 4-18).

As a result, the model was successful in its predictions for the force required to pull the single-ripper-tine under the two experiments' conditions, since the error rate was consistent with the narrow tine force prediction theory, which dictated that the model predictions should be within the difference of ±20% of the measured values for the judgment to be valid.

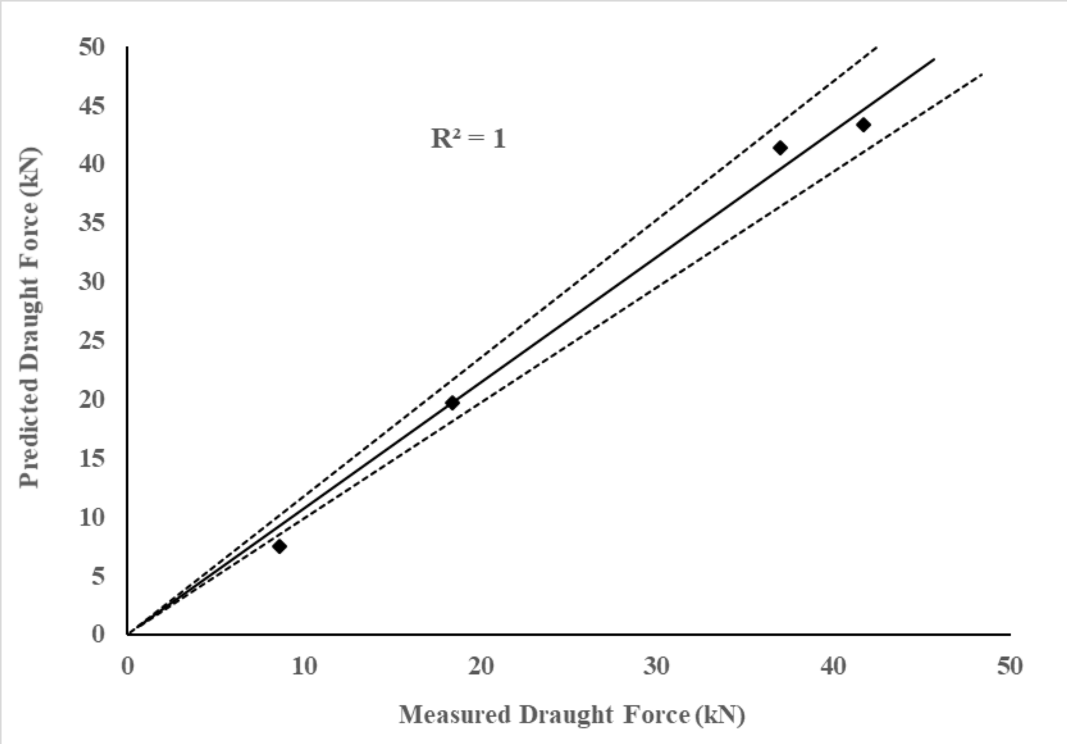

Figure 4-18: Relationship between the predicted and measured draught force (with 8% bounds) for single tine ripper (Barrow) at the Ag plot and Evanslea sites

4.2.3 Conclusion

Adopting an accurate, calibrated and validated model to estimate the required traction force of the agricultural equipment will save a lot of time, effort and money for designers, researchers and owners. The parameters of design and operational conditions of the plough's active section that penetrates the soil and their overlapping with the target soil conditions are considered the essence of any draught force predictive model structure. Almost all predictive mathematical equations that deal with traction force have been reviewed and developed to come up with a universal formulation which is compatible with all tillage equipment via Godwin and O'Dogherty (2007). In addition to its features, this model has recently been developed in the software form to be simplified for users. Due to the lack of sufficient data based on the recommendations of model developers and the Australian agricultural sector researchers, this study had been carried out to validate the G&O tine force model in two dense soils with high clay content. After field implementation, and laboratory and office calculations, the study comes to the following conclusions:

- Under the circumstances of this study, the model prediction error boundaries were within the acceptable requirements, therefore it can be judged that the model was successful in prediction and valid for these experiments
- The required draft force increases with increasing ripping depth level.

We recommend conducting further field investigations with a variety of compacted clayey soils and different operational depths that exceed the level of compaction and up to a meter to ensure a correct and final decision. We then recommend employing the valid model to reduce draught force requirement by improving the ripper's active section design. We also recommend conducting more comparison studies between the designed ripper with existing, commercial and traditionally used rippers which should be followed by growing crops to study the rippers' effects on machinery unit, soil and crop performance, as well as the cost and benefits. Finally, the results of these studies should be presented to the farming community to support them in making decisions that are appropriate for the soil, tractors and machinery on their farms.

4.3 Crop performance modelling work

This section includes the simulated values of the grain and biomass yields of the sorghum and wheat for the long-term (37 years and 38 years), as well as the experiment season at the Ag plot and Evanslea locations, respectively under the three tillage conditions. Evaluation of deep tillage effects on crop yields in response to high clay content soils under long-term of climatic conditions, and validation of the APSIM predictions.

4.3.1 Determination of deep tillage effects on crop performance in two Queensland high clay content soils under long-term climatic conditions using APSIM model

4.3.1.1 Ag plot site (1980-2017)

The monthly rates of rain and maximum and minimum temperatures for this period at this site are shown in Figure 3-35. The yearly rates of rain and maximum and minimum temperatures for this period were about 835 mm, 23˚C, and 11˚C, respectively. Summer rains accounted for 42% of the average annual precipitation, which reached 351 mm/year. The largest annual amount of rain occurred in 2010 (1541 mm), while 479 mm was the lowest amount in 1994. In 1991, 2005 and 2017, the highest average annual maximum temperature was recorded (23.9˚C), while the lowest average maximum temperature was 21.3˚C in 1999. Furthermore, in 1998, the highest annual average minimum temperature was recorded (12.7˚C), while the lowest annual minimum average temperature was 9.9˚C in 1994.

- **Simulated sorghum grain yield**

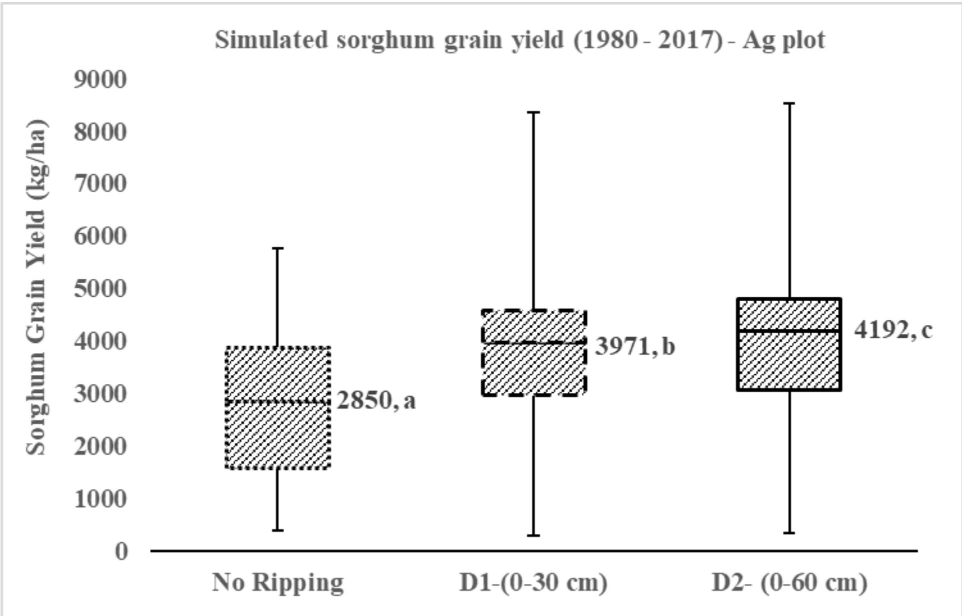

Figure 4-19: Minimum (min), lower quartile (Q1), median (Q2), upper quartile (Q3) and maximum (max) grain yield for 37 years of simulated sorghum-fallow cropping system on a Red Ferrosol soil for ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) at Ag plot site

The plot boxes in Figure 4-19 show the distribution of grain yield data quartiles (or percentiles) for this period. The minimum simulated sorghum grain yield for the C, D1 and D2 during this period were 389 kg/ha, 282 kg/ha and 344 kg/ha, respectively. The maximum predictive grain production for same period was 8529 kg/ha for D2, followed by the D1 with 8365 kg/ha and then the C by 5761 kg/ha. The lower and upper quartiles were 1567 kg/ha, 2956 kg/ha, 3073 and 3879 kg/ha, 4581 kg/ha, 4799 kg/ha for the C, D1 and D2, respectively. Furthermore, the median of the simulated produced grains was 2850 kg/ha, 3971 kg/ha and 4192 kg/ha for the C, D1 and D2, respectively.

The statistical analysis showed that there were significant differences between the mid-point or second quartile (Q2) of the predicted sorghum grain yield under the three tillage conditions. From the table, the simulated median grain yield is seen to have increased by 39% and 47% respectively when ripping changed from C to D1 and then to D2.

- **Simulated sorghum biomass yield**

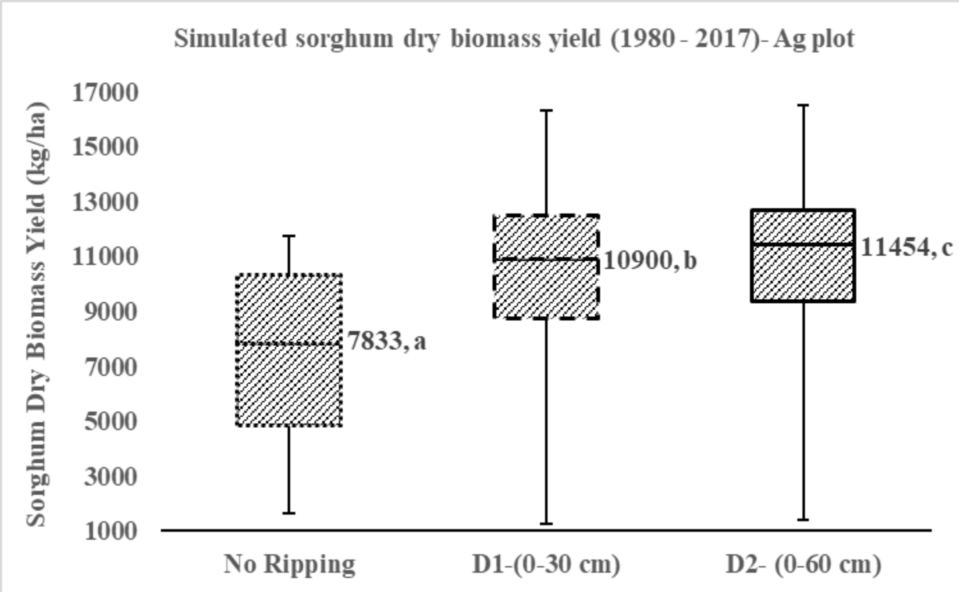

Figure 4-20: Minimum (min), lower quartile (Q1), median (Q2), upper quartile (Q3) and maximum (max) biomass yield for 37 years of simulated sorghum-fallow cropping system on a Red Ferrosol soil for ripping depths (C= no ripping, D1= 0-30 cm, and D2 = 0-60 cm) at Ag plot site

Figure 4-20 summarized the five numbers of the set of simulated sorghum biomass data of 37 years at the Ag plot site on an interval scale using the plot boxes. From the figure, the central value of Control, D1 and D2 was 7833 kg/ha, 10900 kg/ha and 11454 kg/ha, respectively. The highest value of sorghum biomass was 11768 kg/ha, 16318 kg/ha and 16534 kg/ha for the Control, D1 and D2, respectively. The lowest simulated biomass yield was 1650 kg/ha for the zero ripping, followed by D2 with 1396 kg/ha and then the D1 with 1250 kg/ha. The first and third quartile of C, D1, and D2 simulated biomass data were 4824 kg/ha, 8740 kg/ha, 9378 kg/ha and 10317 kg/ha, 12505 kg/ha, 12679 kg/ha for the Control, D1 and D2, respectively.

The statistical analysis showed that there were significant differences between the middle values (second quartile / 50th percentile) of the simulated sorghum biomass yield under the three tillage systems conditions. Compared to the average of non-tillage soil production of biomass, the 0-60 cm ripping system increased biomass production by 46% while the increase was 39% when the ripping system was 0-30 cm.

It can be seen that the model indicated that increased ripping depth led to a significant increase in the yield of biomass.

- **Simulated wheat grain yield**

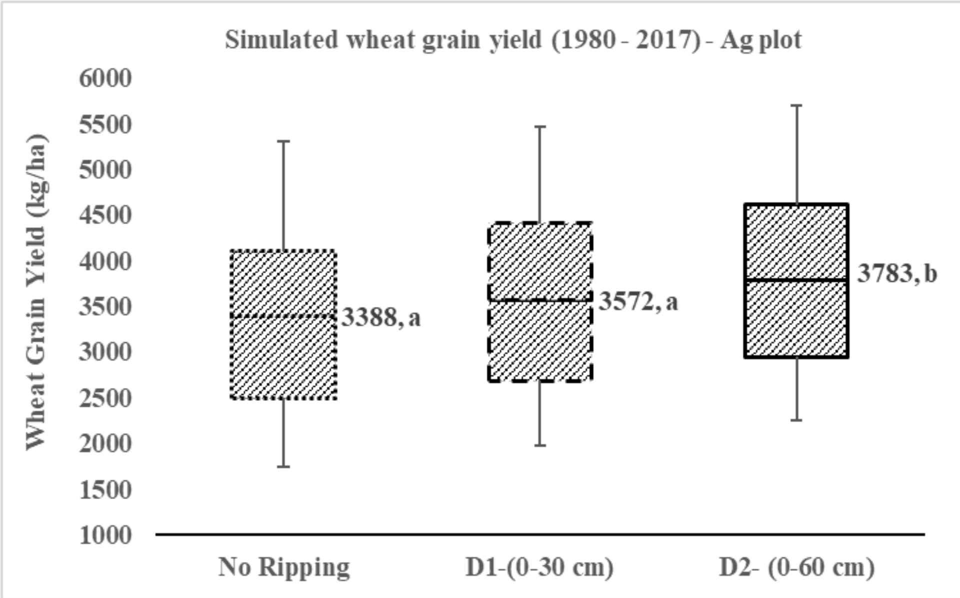

Figure 4-21: Minimum (min), lower quartile (Q1), median (Q2), upper quartile (Q3) and maximum (max) grain yield for 37 years of simulated wheat-fallow cropping system on a Red Ferrosol soil for ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) at Ag plot site

The plot boxes in Figure 4-21 show the wheat grain yield data percentiles distribution from 1980 to 2017. The minimum simulated wheat grain yield was 1748 kg/ha, 1973 kg/ha and 2247 kg/ha for C, D1 and D2, respectively. The lower quartile was 2492 kg/ha, 2683 kg/ha and 3073 kg/ha for the C, D1 and D2, respectively. After, the median of the simulated grains was 3388 kg/ha, 3572 kg/ha and 3783 kg/ha for C, D1 and D2, respectively. Then and in order, the upper quartile was 4102 kg/ha, 4409 kg/ha and 4609 kg/ha for C, D1, and D2, respectively. Finally, the maximum predictive grain production for same period was 5310 kg/ha for the Control followed by D1 with 5469 kg/ha and then D2 with 5706 kg/ha.

The statistical analysis shows that there is no significant difference between the simulated data of the 0-30 cm and the zero ripping systems. However, the statistical analysis shows that there are significant differences between the middle of the simulated wheat grain yield under D2 and the two other tillage systems' yield middles.

In comparison to zero and 0-30 cm ripping, the ripping depth of 0-60 cm increased the total grain production by 12% and 6%, respectively.

- **Simulated wheat biomass yield**

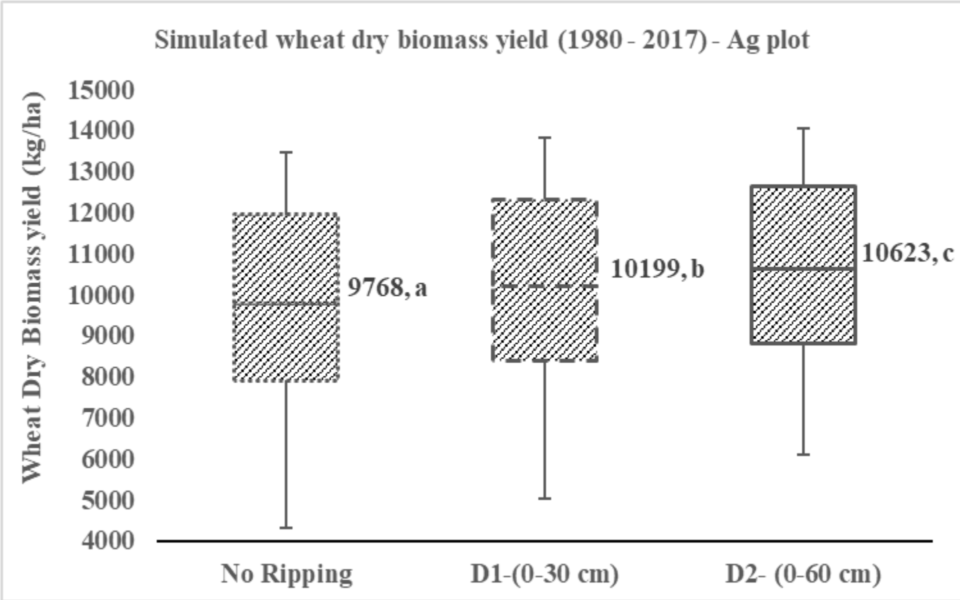

Figure 4-22: Minimum (min), lower quartile (Q1), median (Q2), upper quartile (Q3) and maximum (max) biomass yield for 37 years of simulated wheat-fallow cropping system on a Red Ferrosol soil for ripping depths (C= no ripping, D1= 0-30 cm, and D2 = 0-60 cm) at Ag plot site

Figure 4-22 presents the wheat biomass dataset simulation for 37 years (1980 – 2017) at the Ag plot site in five numbers (the central number and its four variabilities) through the boxplot graph. The box plots show that switching from zero ripping to 0-30 cm then to 0-60 cm, increased the lowest quartile of wheat biomass from 4302 kg/ha to 5034 kg/ha and then to 6081 kg/ha and the highest quartile from 13455 kg/ha to 13804 kg/ha, and then to 14057 kg/ha, respectively. In the same way, system switching led to an increase in the wheat biomass lower quartile from 7909 kg/ha to 8377 kg/ha and then to 8808 kg/ha, and the higher quartile from 11940 kg/ha to 12325 kg/ha and then to 12627 kg/ha, respectively. The median values also experienced the same scenario, where biomass increased from 9768 kg/ha to 10199 kg/ha and then to 10623 kg/ha when the tine penetration increased from 0 cm to 30 cm and then to 60 cm.

Under the three different ripping systems, the statistical analysis shows that there were significant differences between the 50th percentiles of the simulated wheat biomass yield. Compared to the average of zero ripping production of biomass, D2 ripping increased biomass production by 9% while the increase was 4% when D1 was adopted.

4.3.1.2 Evanslea site (1980-2018)

The monthly averages of rains and maximum and minimum temperatures for this period at this site are shown in Figure 3-36. The annual rates of rain and maximum and minimum temperatures for this period were around 584 mm, 26˚C, and 12˚C, respectively. Summer rains accounted for 40% of the average annual precipitation, which reached 233 mm/year. The lowest annual amount of rain occurred in 2000 (394 mm), while 2010 saw the most rain, 967 mm. Further, 2010 experienced the lowest average yearly maximum temperatures (24.6˚C), whereas the maximum temperature average reached 27˚C or slightly more during 2002, 2005, 2017 and 2018. Furthermore, in 1994 the lowest average yearly minimum temperature was recorded (10.2˚C), and the minimum temperature average reached 12.5˚C or slightly more during the years 1998 and 2010.

- **Simulated sorghum grain yield**

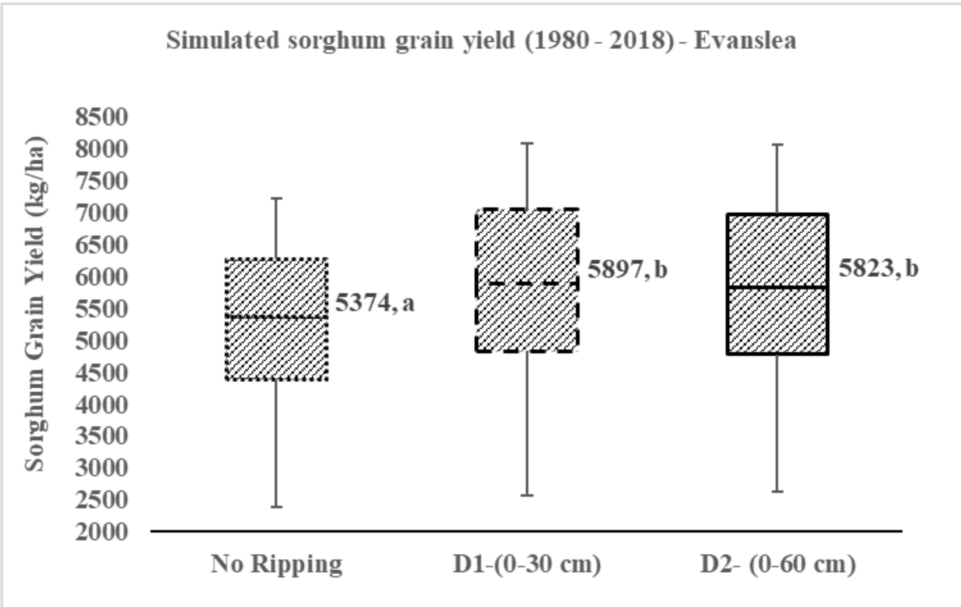

Figure 4-23: Minimum (min), lower quartile (Q1), median (Q2), upper quartile (Q3) and maximum (max) grain yield for 38 years of simulated sorghum-fallow cropping system on Black Vertosol soil for ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) at Evanslea site

The plot boxes in Figure 4-23 show sorghum grain yield data percentiles distribution from 1980 to 2018. The minimum simulated grain yield was 2379 kg/ha, 2563 kg/ha and 2635 kg/ha for C, D1 and D2 during this period, respectively. The lower quartile was 4391 kg/ha, 4831 kg/ha, and 4782 kg/ha for C, D1 and D2, respectively. The median of the simulated grains was 5374 kg/ha, 5897 kg/ha, and 5823 kg/ha for C, D1 and D2, respectively. The upper quartile was 6278 kg/ha, 7051 kg/ha, and 6977 kg/ha for C, D1 and D2, respectively. Finally, the maximum predictive grain production for same period was 7233 kg/ha for C, followed by D1 with 8080 kg/ha and D2 with 8057 kg/ha.

The statistical analysis of simulated median grain yield showed that there was no significant difference between the yield of the 0-30 and 0-60 cm ripping systems. However, the statistical analysis also showed that both depths showed a significant difference in grain production compared with the control soil. In comparison to the zero ripping system, the ripping depth of 0-30 and 0-60 cm improved the average grain yield by 10 and 8%, respectively.

- **Simulated sorghum biomass yield**

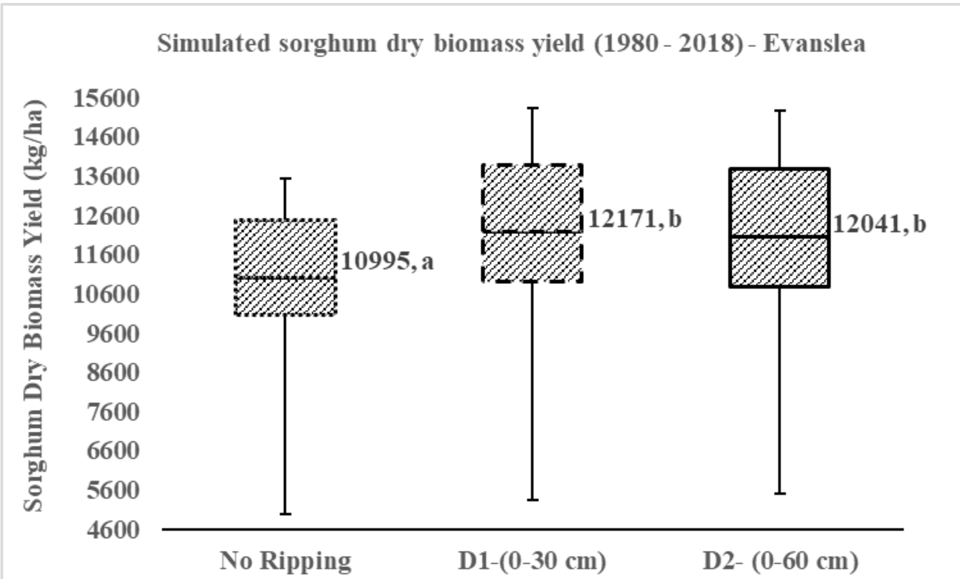

Figure 4-24: Minimum (min), lower quartile (Q1), median (Q2), upper quartile (Q3), and maximum (max) biomass yield for 38 years of simulated sorghum-fallow cropping system on a Black Vertosol soil for ripping depths (C= no ripping, D1= 0-30 cm and D2 = 0-60 cm) at Evanslea site

Figure 4-24 presents and summaries the sorghum biomass dataset simulation for 38 years (1980 - 2018) at Evanslea site in five-numbers (the central number and its four variabilities) using the boxplot graph. From the figure, the central value of C, D1 and D2 was 10995 kg/ha, 12171 kg/ha and 12041 kg/ha, respectively. Also, the highest value of biomass was 13534 kg/ha, 15320 kg/ha and 15278 kg/ha for C, D1 and D2, respectively. The lowest simulated biomass yield was 4997 kg/ha for C, followed by the D1 with 5361 kg/ha and then the D2 by 5516 kg/ha. The first (Q1), and third quartile (Q3) of the simulated biomass production were 10065 kg/ha, 10901 kg/ha, 10783 kg/ha and 12477 kg/ha, 13878 kg/ha, 13778 kg/ha for C, D1 and D2, respectively.

The statistical analysis showed that there was no significant difference between the simulated median biomass yield of the 0-30 cm and 0-60 cm ripping systems. However, the analysis showed that both depths had a significant difference when comparing their production with that of the control soils. Compared to the average of control soil production of biomass, the 0-60 cm ripping increased production significantly by 10%, while the significant increase was 11% for ripping at 0-30 cm. Both ripping depths had a positive effect on this feature during the period of study.

4.3.2 Investigation of Agricultural Production Systems Simulator (APSIM) predictability of deep tillage effects on sorghum and wheat yields in two Queensland high clay content soils

Crop yield results were extracted from the model's long-term predictions for the trial seasons and compared with the experimental results to verify the validity of the model's work. This section contains a comparison between the real values of grain and biomass yields against the corresponding modelled values with an error rate to verify model suitability.

4.3.2.1 Ag plot site (2017)

The 2017 monthly rains, maximum and minimum temperatures at the Ag plot site are shown in Figure 3-35. Total rain and maximum and minimum temperatures for this year were 867 mm, 23.9˚C and 11.4˚C, respectively. The 2017 climate values of rain and maximum and minimum temperatures were higher than the average of their counterparts in the long-term climate at rates of 4%, 4%, and 1%. Although, the 2017 rains were 32 mm higher than the annual long-term rainfall, the summer rains accounted for 28% of the total annual precipitation, which reached 244 mm. The largest monthly amount of rain occurred in March (304.2 mm), while 0.7 mm was the lowest in September. On the other hand, in February, the highest monthly maximum temperature was recorded (31.4˚C), while the lowest maximum temperature was 18.1˚C in June. Furthermore, in January, the highest monthly minimum temperature was recorded (18.6˚C), while the lowest monthly minimum temperature was 2.6˚C in August.

- **Simulated sorghum grain yield**

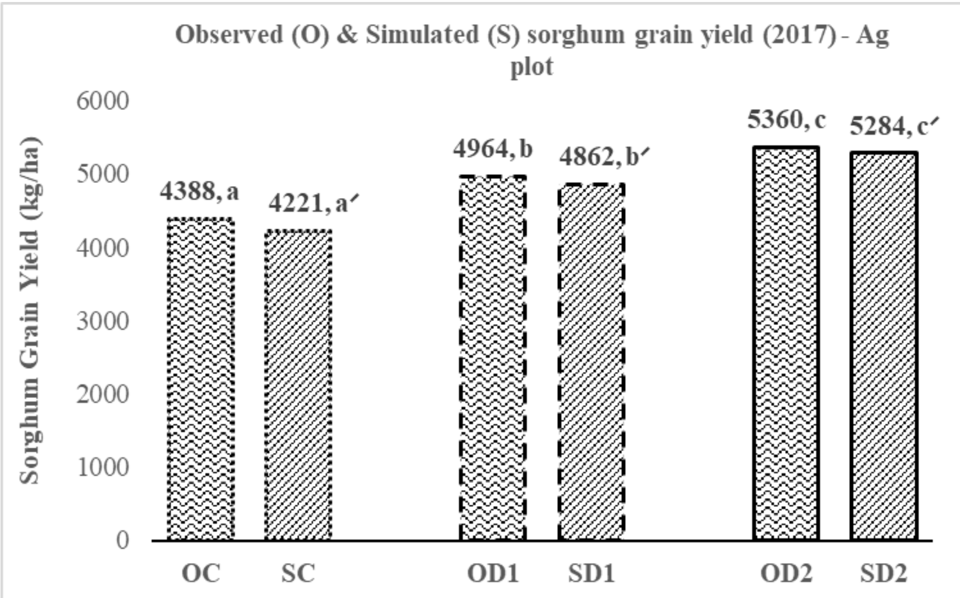

Figure 4-25: Observed (O) and Simulated (S) sorghum grain yield under the C, D1 and D2 Ag plot site during 2017 experiment season

The model results after simulating the overlap between the 2017 climate, conditions of each ripping depth, in addition to the used field practices, are shown in Figure 4-25. The model's simulation results were close to the measured field values of C, D1 and D2 with a difference of 3.8%, 2.1%, and 1.4%, respectively (as shown in Appendix G.1.1).

Furthermore, the statistical analysis of the simulated data shows that the soil conditions after the D1 and D2 system both achieved a significant increase in grain yield compared to the grain production of the unripped soil. From the figure, the simulated grain yield increased from 4221 kg/ha to 4862 kg/ha (15%) and then to 5284 kg/ha (25%) when the model input soil conditions were changed from no ripping to ripped with a depth of 0-30 cm and then to ripped with a depth of 0-60 cm, respectively. Although there were variances between the real and estimated values of grain yield, the model was accurate in simulating the effect of ripping depth on final grain productivity.

- **Simulated sorghum biomass yield**

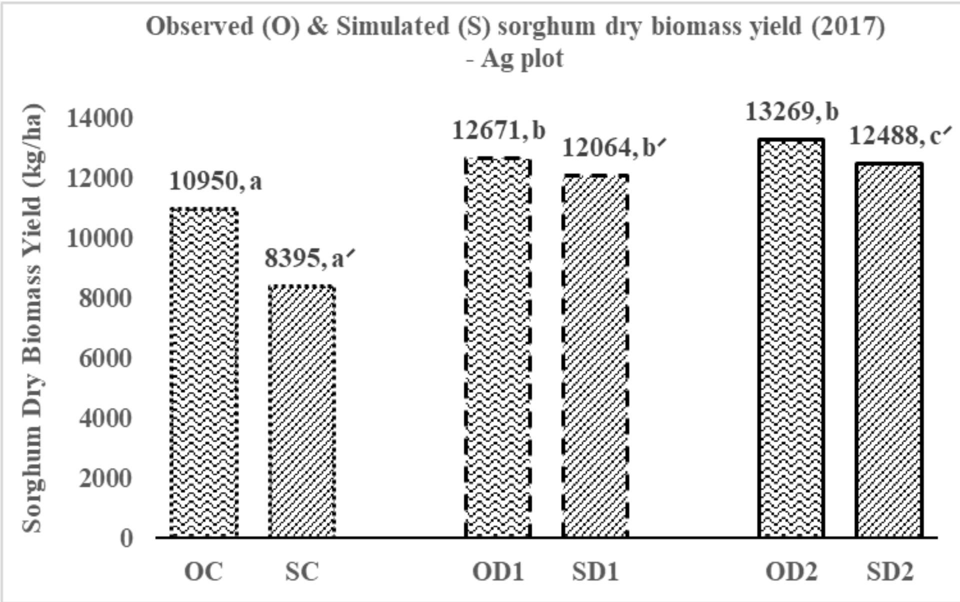

Figure 4-26: Observed (O) and Simulated (S) sorghum biomass under the C, D1 and D2 Ag plot site during 2017 experiment season

The Figure 4-26 shows the simulated biomass of sorghum under C, D1 and D2 at the Ag plot site during the 2017 experiment year. According to Appendix G.1.2, the model expectation for the biomass yield under uncultivated and compacted soil was 23% less than the corresponding actual value. Predictions under the ripping soil conditions were close to the field values, with an approximate difference of 5% and 6% for the first and second ripping depths, respectively. From the figure, the simulated statistical analysis was not in line with the analysis of real statistical data regarding the significance absence between the D1 and D2, however it was agreed that both of them have increase the biomass yield significantly compared to the C's production. Through the figure and the appendix, and by arranging the biomass yield quantity in ascending order, it can be concluded that the ripping systems with a depth of 30 and 60 cm have both achieved a significant increase in comparison to the Control's biomass yield (8395 kg/ha), with an approximately of 44% (12064 kg/ha) and 49% (12488 kg/ha) increase, respectively.

- **Simulated wheat grain yield**

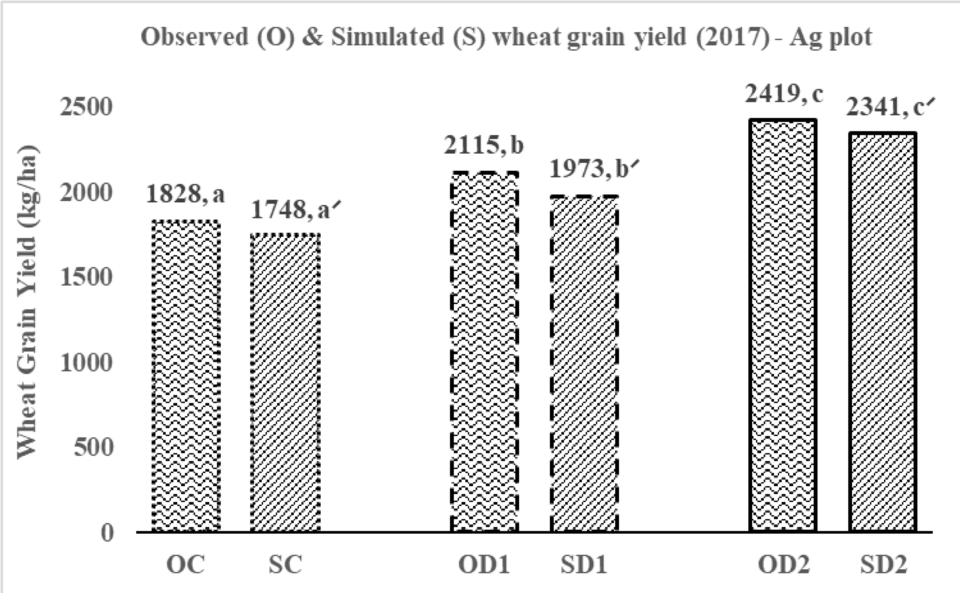

Figure 4-27: Observed (O) and Simulated (S) wheat grain yield under C, D1 and D2 at Ag plot site during 2017 experiment season

The APSIM model simulations of wheat grain yield under the experiment circumstances at the Ag plot site in 2017 for the three ripping conditions are shown in Figure 4-27. The model's expectations agreed with the measured values, where they were 96%, 93% and 97% for C, D1 and D2, respectively as detailed in Appendix G.1.3. Likewise, the analysis of statistically simulated data was identical to the field data statistical analysis, which concluded that D1 and D2 both had the effect on increasing the grain yield of standard or control soil significantly. In comparison with the control soils' grain productivity, the figure indicates that increasing the ripping depth from 30 cm to 60 cm resulted in production increasing from 1748 kg/ha to 1973 kg/ha (13%) and then to 2341 kg/ha (34%), respectively. Again, analysis of results showed that the predicted values were lower than the experiment values.

- **Simulated wheat biomass yield**

Figure 4-28 shows the observed wheat biomass yield at the Ag plot site during the 2017 season, as well as the simulated yield of biomass after input of experiment data.

Appendix G.1.4 indicates that the model was varied in its simulations of produced biomass amount, as they were around 4% and 6% lower than the productivity of C and D1, respectively while D2 productivity was 2% higher.

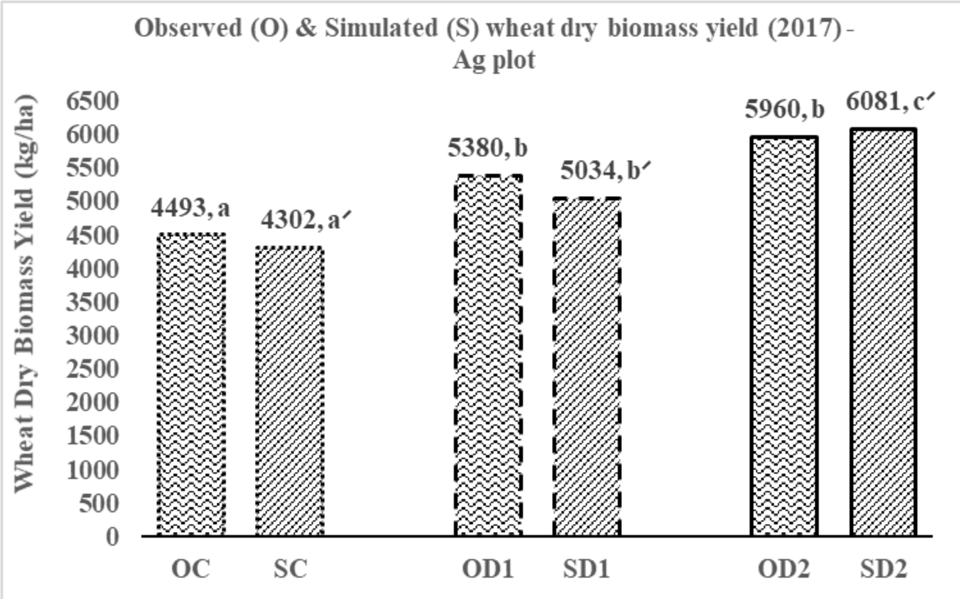

Figure 4-28: Observed (O) and Simulated (S) wheat biomass yield under the C, D1, and D2 at Ag plot site during 2017 experiment season

Simulated data analysis was also inconsistent with the statistical analysis of field experiment data, where the analysis indicated that there were significant differences between the three tillage systems with respect to model data while there was no significant difference between depths of 30 cm and 60 cm with respect to field data. From the figure, the simulated biomass yield increased from 4302 kg/ha to 5034 kg/ha (17%) and then to 6081 kg/ha (41%) when the model input soil conditions were changed from no ripping to ripped to a depth of 0-30 cm and then to ripped with a depth of 0-60 cm, respectively. Although the model oscillated in its simulation of the wheat biomass yield, its results were not far from the real values and within acceptable limits as well.

4.3.2.2 Evanslea site (2018)

Monthly rain and maximum and minimum temperatures for Evanslea in 2018 are shown in Figure 3-36. The total and summer rainfall as well as the rate of maximum and minimum temperatures for this year were 454 mm, 200 mm, 27˚C, and 11.4˚C, respectively. In comparison to the average climate for the 38 years (1980-2018), the

2018 climate was characterised by a decrease in annual rainfall and summer rainfall, and average minimum temperature by 22%, 14%, and 2%, respectively, while the average maximum temperature was 3% more than its counterpart for the long-term climate. It is worth noting that more than half of the 2018 total rain (56%) occurred during the summer months (December, January and February). The highest monthly amount rainfall occurred in October (136.3 mm), while 0.6 mm was the lowest amount in May. Moreover, the highest maximum recorded temperature during this year at this site was (33.7˚C) in January, while in June 2018, the lowest monthly maximum temperatures was recorded (20.4˚C). Furthermore, in August, the lowest monthly minimum temperature was recorded (2.3˚C), while the highest minimum recorded temperature was 18.3˚C in January.

- **Simulated sorghum grain yield**

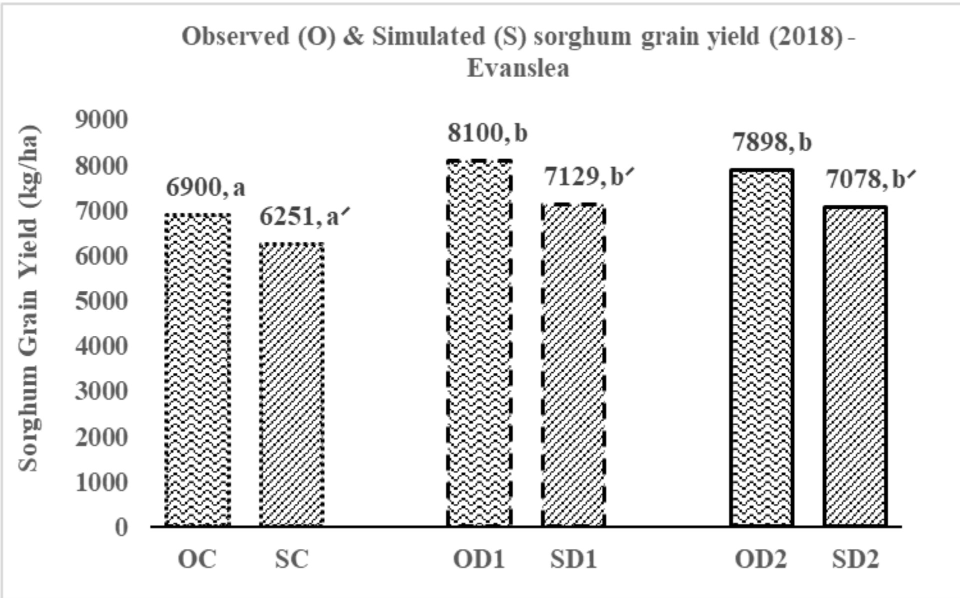

Figure 4-29: Observed (O) and Simulated (S) sorghum grain yield under the C, D1 and D2 at Evanslea site during 2018 experiment season

The APSIM model simulations of sorghum grain yield under the experiment at the Evanslea site in 2018 for the three ripping system soil conditions are shown in Figure 4-29. Through Appendix G.2.1, the model's expectations after being fed with data were, in general, lower than the measured data by around 9%, 12% and 10% for C, D1 and D2, respectively. Likewise, the analysis of statistically simulated data was identical to the field data statistical analysis, which concluded that D1 and D2 both had the significant effect on increasing the grain yield compared to zero ripping production. From the figure and the appendix, in comparison with the productivity of zero ripping (6251 kg/ha), the shift to 30 cm ripping depth resulted in an increase in grain yield by approximately 14% (7129 kg/ha), while the increase was in the range of 13% (7078 kg/ha) when the ripper depth was 60 cm. From the above, the 30 cm ripping depth had achieved an increase in grain production compared to depth of 60 cm, but this rise was not significant.

- **Simulated sorghum biomass yield**

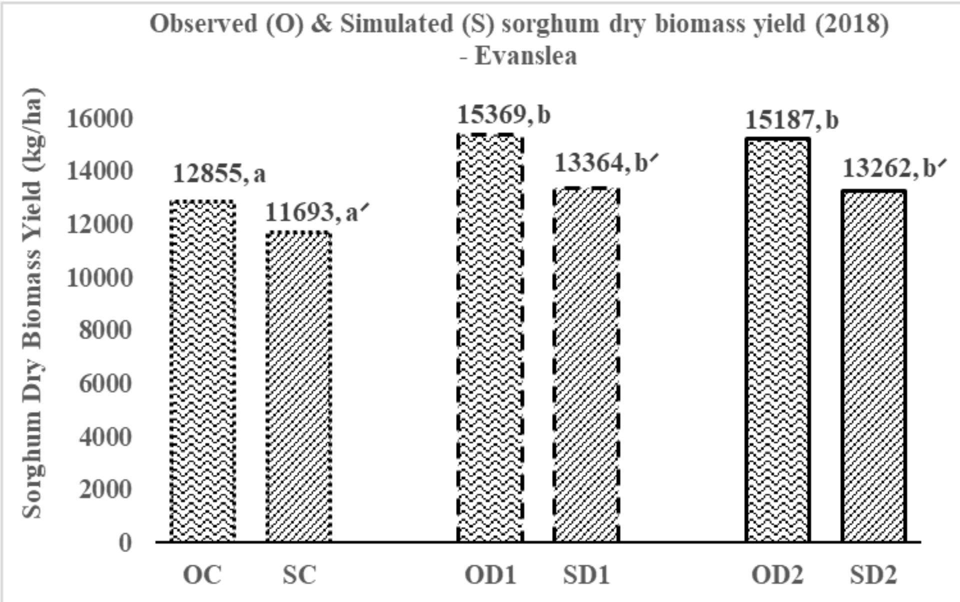

Figure 4-30: Observed (O) and Simulated (S) sorghum biomass yield under the C, D1 and D2 Evanslea site during 2018 experiment season

The model's results, after simulating the overlap between the 2018 climate, the conditions of each soil, in addition to the field practices used, are shown in Figure 4-30. As shown in Appendix G.2.2, the model outcome values were lower than the real values, however the simulated results were close to the measured field values with a difference of 9%, 13% and 12.7% for C, D1 and D2, respectively. Furthermore, the statistical analysis of the simulated results shows that the soil conditions after D1 and D2 both achieved a significant increase in biomass yield compared to the no ripping. From both the figure and appendix, the simulated biomass yield increased from 11693 kg/ha to 13364 kg/ha (14%) and then to 13262 kg/ha (13%) when the model input soil conditions was changed from no ripping to ripped with a depth of 0-30 cm and then to ripped with a depth of 0-60 cm, respectively. From the above, the 30 cm ripping depth increased biomass production compared to the depth of 60 cm, but this increase was not significant. Although there were variances between the experiments and model results, the model was accurate in simulating the effect of ripping depth systems on soil productivity.

Discussion

For both sites, the APSIM model results closely followed the results of the field trials; validating and calibrating the model. Upon reviewing the literature, we have discussed that previously, the APSIM modules have been validated for different soils, climates, and management conditions by a number of researchers, in addition to Table 2-2; Hammer et al. (1995); Moore et al. (1997); Probert, Carberry, et al. (1998); Dolling et al. (2005); Peake, Whitbread, et al. (2008); Huth, Banabas, Nelson, and Webb (2014). Similarly, the data of the current study have been employed for a validity check of the wheat and sorghum modules in the APSIM model.

Both locations were different in several aspects in terms of experimental conditions - including differences in average annual rainfall, maximum and minimum temperatures, the type of clay soil, soil texture, and soil physical properties, etc., as well as the established farm system which were random at the Ag plot and controlled at the Evanslea farm. The sites were also different in sowing rate and space during planting as well as in field practices across the planting seasons. Consequently, there were differences in the quantities of grain and biomass in relation to the sorghum crop, which can be considered reasonable and acceptable in this study. On a large scale, the current study conditions also differed from many other field study conditions. The variances between this study and the other studies conducted in the region in production data between the two study crop types (wheat and sorghum) may also be regarded as reasonable.

Despite the fact that the climatic conditions varied, whether in the long- or short-term between the two study sites, the modelling results indicated that the soil physical properties improvement following the deep tillage operation was probably the most effective influence in increasing the crop grain and dry matter yield. Therefore, it was noticed, through the model's long-term results, that the control soils suffered a marked decrease in their productivity during the dry years, when rainfall was below the annual rate, while the treated soils did not suffer a sharp drop.

Mitigation of soil strength or compaction will improve crop production through the reduction of runoff and erosion (Connolly et al., 1997), increased rainfall infiltration and soil water storage (Barraclough & Weir, 1988), promotion of root elongation for water absorption (Busscher et al., 2001), and enhanced soil dissolved nutrient uptake through absorption via root penetration (Miransari et al., 2009; Wolkowski, 1990) or movement to the root zone through micro soil pores via the capillary action of water flowing upward (Divito, Rozas, Echeverría, Studdert, & Wyngaard, 2011). Accordingly, tillage below root zone will increase the volume of the soil, its pores, the penetrated and stored water, the dissolved nutrients, as well as the roots, which in turn enhances the efficiency of water and fertiliser use and nutrient absorption by the plant (Probert et al., 1995), thus improving both quantity and quality of soil production as seen in the literature review chapter.

In rain-fed farmland, in particular those located in arid and semi-arid regions, the availability of appropriate soil stored moisture at sowing time determines crop efficiency and its production (Freebairn, Wockner, Hamilton, & Rowland, 2009; Júnnyor et al., 2015), otherwise seed will suffer stress and thirst in the germination stage due to the high tensile bonds between the soil particles and surrounding sticking water minutes (Probert et al., 1995). As well, rainfall on loosened land will enhance the water movement downwards and reduce the horizontal runoff causing erosion (Acuña, Lisson, Johnson, & Dean, 2015; Connolly et al., 1997; Hammer et al., 2010). Water availability, insufficiency or scarcity at the seed planting time will have a key impact on seed creation and subsequent phases, so the model results will vary as well (Kodur, 2017). Therefore, grain and biomass yield reduction were one of the most expected consequences of not improving the physical soil properties via deeply tillage.

From this study, compared to control or zero ripping soils, the model estimations regarding the high productivity of ripped soils are in line with many cereal experiments around the world such as Holloway (1996), Olesen and Munkholm (2007), Gill et al. (2012), Roper et al. (2015) and Armstrong et al. (2017).

The rate of sorghum seeds planted at the Ag plot site during 2017 was 72,700 seed/ha, total annual rain was of 876 mm, while 70,100 of the same sorghum variety seeds were planted per hectare at Evanslea site during 2018 with a precipitation amount of 454 mm. However, the productivity of the Evanslea site was the highest of all experimental treatments and, when considering that both soils are clayey but different in classification, the low capacity of Red Ferrosol soil for rain water could be due to compaction (Bell et al., 1997; Bell et al., 1995; Bell et al., 1998), as well as to high drainage when it loosen (Bell et al., 1996; Hussein, 2018) which considered one of the Red Ferrosol key characteristics (Bridge & Bell, 1994). Also, the system of farming which was random, may have had an important effect on lowering soil productivity (Radford, Yule, McGarry, & Playford, 2001; Smith et al., 2014; Tullberg et al., 2007). In addition, crop service operations on the Evanslea commercial farm, such as control of weeds, diseases and insects, as well as supplementary fertilisation, could not be applied to the Ag plot's crops. This may also be an explanation for the Ag plot wheat productivity, which was somewhat low compared to a number of Australian wheat studies such as Freeman et al. (2007), Gill et al. (2008), Gill et al. (2012), Moosavi et al. (2013) and Celestina et al. (2018).

After feeding the APSIM model with sorghum soils' data for the two sites, PAWC for the Ag plot soil varied (143±20 mm water) and less than Evanslea soil's PAWC soil which was more stability and high (272±1 mm water), this indicates that the model is sensitive and confirms what was listed above.

At Evanslea, the D1 sorghum grain and biomass yield was higher than D2 production. However, this increase was not statistically significant which may be due to the decrease in the amount of water available for the plants because the rain water penetrates deep into the D2 soil due to the deep ripping level. The results of the model came after feeding to confirm this, as the amount of water available to the plant (PAWC) was 272.7 mm and 270 mm water for both D1 and D2, respectively.

Most Australian applied crop models' outputs, including APSIM, do not fully match with field data. The waterlogging, inefficiency of water, diseases, insects, weeds, N deficiency, sodicity, acidity, salinity, and losses of mechanical harvest are facts that may hinder plant growth, however they are not considered priorities of the model when applied (Cornish & Murray, 1989; Hochman et al., 2009; Mercau et al., 2007; Sadras et al., 2003; Whish et al., 2007). Also, in this study there is a gap between the experiments and simulated values. Most model results were lower than the observed values. This may be due to the absence of harvest losses since harvest was manual and its results are considered acceptable (Carberry et al., 2009), In addition, the moisture of harvested crop yield was corrected according to the standard moisture for commercialization of wheat (12.5%) and sorghum grain (13.5%), therefore there was an average increase in the weight of the yield by 1.85%, 2.27%, and 4.63% for the Ag plot sorghum, wheat, and the Evanslea sorghum, respectively.

Supporting the model sections with adequate, detailed and accurate data can reduce the difference between the real and simulated values (Carberry et al., 2009; Carberry et al., 2002; Probert et al., 1995; Rykiel, 1996). However, it is possible to judge that the model is valid when the difference between the experimental and model values is ≤ 30% or when the regression is ($0.65 \leq$ regression $R^2 \leq 1$) (Connolly et al., 2001; Hearn, 1994; Peake, Robertson, et al., 2008). Accordingly, in this study, the APSIM model was successful in its predictions of dry grain and biomass yield of wheat and sorghum crops in both locations. In general, the average of APSIM simulation error was ±7% and the R^2 was 0.98 (Figure 4-31).

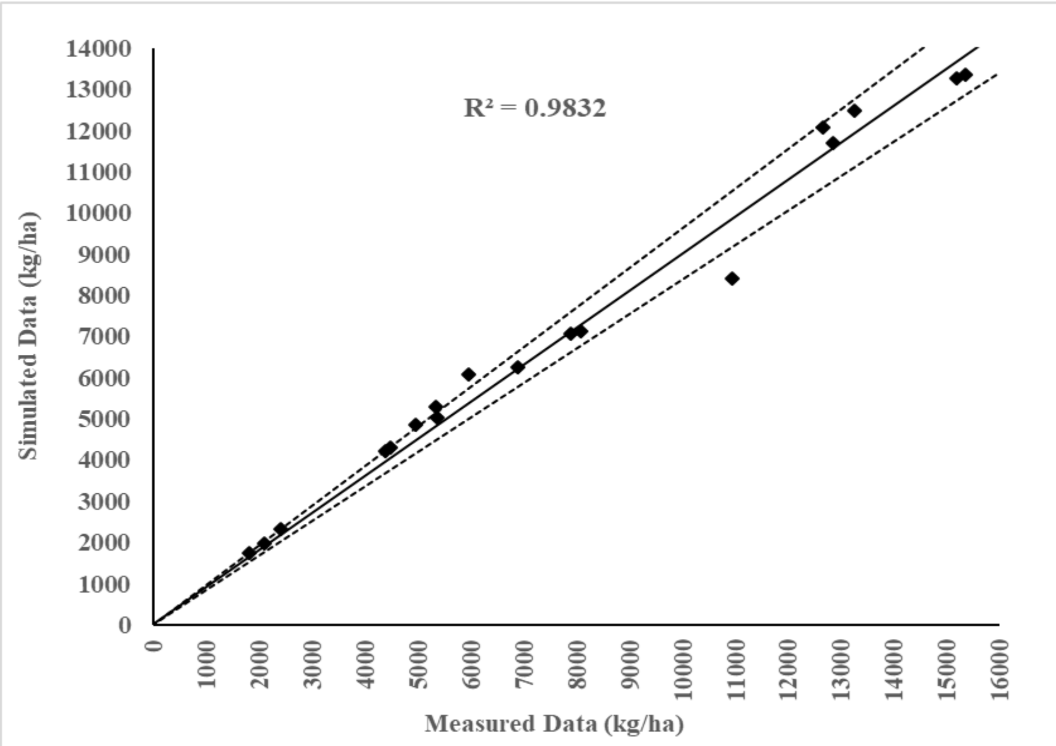

Figure 4-31: Relationship between the simulated and measured production (with 7% bounds) for two Toowoomba study sites soils

These experiments have highlighted the deep tillage effect on the two heavy, clay soils' productivity with different textures and under two different farming systems however, there is an urgent need to conduct the same research on CTF and RTF farms with black or grey Vertosols since these soils dominate large areas of Queensland land devoted to the production of important and economic crops such as cotton and cereals, and to support the Australian agricultural sector in taking the right decisions in the face of immediate and future risks such as global warming and soil compaction by employing and enriching the model with sufficient data for deep ripping of clay soil which is considered important though rarely practised.

4.3.3 Conclusion

In this study, a novel modelling approach using APSIM has been developed to quantify possible increases in grain and biomass yield of Red Ferrosol and Black Vertosol clayey Queensland soils via improving their physical properties through deep ripping for long and short term. Consequently, it is considered complementary to recent studies and investigations in this field (Antille, Huth, et al., 2016; Hussein, 2018). The main conclusions derived from this study are:

- The productivity of sorghum and wheat crops in rain-fed southeast Queensland has been found to be closely related to the improved physical soil conditions provided by deep tillage
- The deep ripping system has the potential to improve soil aeration and drainage, and increase rain-water storage capacity by improving filtration and reducing runoff, thus creating an abundance of water during the planting and growing stages, with the possibility of stimulating root elongation to access stored water in drought conditions
- In Red Ferrosol soil under RTF and climatic conditions that spanned 37 years (1980 - 2017) at the Ag plot site, compared to the average production of compacted (zero ripping) soil, D2 (0-60 cm) achieved the highest and significant average of predicted grain (4192 kg/ha) and biomass (11454 kg/ha) yield of sorghum (first crop after ripping) with a difference of 47% and 46%, respectively, while D1 (0-30 cm) achieved the second largest significant average amount of sorghum grain (3971 kg/ha) and biomass (10900 kg/ha), with a difference of 39% compared with the control treatment (2850 kg/ha and 7833 kg/ha, respectively)
- Also, at the Ag plot site, for the second crop after ripping (wheat), D2 (0-60 cm) achieved the highest and significant average of predicted wheat grain

(3783 kg/ha) and biomass (10623 kg/ha) yield with a difference of 12% and 9%, respectively compared to the average production of the C soil, while D1 achieved a significant increase of predicted wheat biomass average (10199 kg/ha) with a difference of 4% compared to non-ripped soil, while its average predicted of wheat grain yield (3572 kg/ha) was not significant in difference compared to the control treatment (3388 kg/ha and 9768 kg/ha, respectively)

- In Black Vertosol soil under CTF and climatic conditions that lasted for 38 years (1980 - 2018) at the Evanslea site, compared to the average production of zero ripping soil, D1 (0-30 cm) achieved the highest and significant average of predicted grain (5897 kg/ha) and biomass (12171 kg/ha) yield of sorghum with a difference of 10% and 11%, respectively, while D2 (0-60 cm) achieved the second highest significant average amount of sorghum grain (5823 kg/ha) and biomass (12041 kg/ha), with a difference of 8% and 10% respectively, compared with the non-ripped treatment (5374 kg/ha and 10995 kg/ha, respectively)
- Under the circumstances of this study, the model prediction error scope and the regression R^2 value of the measured and simulated values are within the acceptance requirements, therefore the model can be judged to be successful in prediction, and valid for these experiments.

5. CONCLUSIONS

Based on the research aims and objectives outlined in **Chapter 1**, the conclusions below have been drawn. They are based on the detailed results included in **Chapter 4** and the conclusions in Sections 4.1.5, 4.2.3, and 4.3.3. After presenting the conclusions, a set of practical recommendations is provided in **Chapter 6**.

5.1 Evaluation of deep tillage system impact on soils and crops, and benefits at two Queensland farms with high clay content soils

This study found the following:

- Under subtropical and relatively dry environmental conditions, the deep tillage improved the physical properties and crop production of both rain-fed South East Queensland clayey soils under CTF and RTF systems
- The improvement value increased as the depth of deep tillage increased
- The draught requirement increased with increasing tillage depth and clay fraction. Under RTF and RTF systems, the required energy doubled when the tillage depth doubled (changed from 30 cm to 60 cm). As a result, the cost of deep tillage was greater when the 0-60 cm depth was applied at both farming systems
- Despite the higher application costs, the achieved total income covered these costs and made deep tillage a productive and profitable practice
- Although the application of optimal N fertiliser rates increased grain yield and yield components at the Ag plot RTF site, it was not a profitable practice for unripped (compacted) soil
- The study showed that deep tillage for both sites was a productive and profitable practice. As it was characterised by the lowest total cost and highest yield, deep tillage was more beneficial in the CTF system during this study.

5.2 Investigating the Godwin and O'Dogherty single tine model's validity in two Queensland high clay content soils

This study found the following:

- At both the Ag plot and Evanslea soils, the G&O single tine predictive model outcomes showed a good agreement with the measured draught force readings.

The model errors were within the margin of error found for other soils in the original work (±20%)

- The results of the experiments and the G&O model were showed that the relationship between draught force value and operating depth is linear
- Under the circumstances of this study, it appears that, the mechanism of the G&O model was stable and can be used to support further studies and
- It could also be a practical and novel approach to add to farm decision-making tools if it is acknowledged as useful.

5.3 Determination of deep tillage effect on crop performance in two Queensland high clay content soils using long-term APSIM simulations

The main outcomes of long- term simulations are:

- On both rain-fed South East Queensland clayey soils under CTF and RTF systems, practiced deep tillage had significantly improved and increased cereal crop yields stability. However, the improvement rates were sizeable and more pronounced in the RTF system
- Through long-term evaluation, deep tillage can, therefore, be considered an efficient approach for the establishment of successful crops with stable, abundant production and high farm income.

5.4 Validation of APSIM predictability of deep tillage effects on sorghum and wheat yields in two Queensland high clay content soils

The investigations' findings of APSIM predictability are summarised below:

- Overall, most of APSIM's outputs were less than the field experiments values but consistent with study context
- APSIM simulation results were quite consistent with the observed grain yield and yield components of ripped and unripped plots at both Red Ferrosol and Black Vertosol soils. Based on previous and current studies, the model errors were within the acceptable error limits

- Accordingly, the model was successful in representing the environment of ripped and non-ripped soils and the surrounding environmental climates on crop performance, so its values were comparable and close to reality
- Under the circumstances of this study, the model seems to be effective and could be used to assess further deep tillage studies as well as contribute to farm decision making.

When correctly implemented, deep tillage is an effective technique for alleviating compaction and restoring the physical condition of soil to support profitable production. Adoption of this strategy by farm management can be pre-assessed by applying the modelling approach employed in this study which relied on APSIM and the force prediction model of Godwin and O'Dogherty.

In particular, the findings confirm the hypotheses that were formulated before conducting the study, and thus support the necessity of applying deep tillage in South East Queensland clay soils for cereal and row cropping systems under both CTF and RTF. Based on field experiments, modelling work and the conclusions reached by this study, a number of practical recommendations that would raise the management efficiency of such soils are included in the next chapter. Some soils, crops and objectives that require further research will be discussed and recommended.

6. RECOMMENDATION AND FUTURE WORK

The following recommendations for future work come from this study:

- Deep tillage greatly improved soil quality, crop quantity and farm profits through improved soil-building and physical properties, crop performance and subsequent production. And unmistakable sign that deep ripping has a positive effect on improving the surrounding environment quality. Obviously, these gains are accentuated more when the practice was applied within CTF system or with the best dose of N fertiliser. There is a need to re-evaluate the study for cracked Vertosols for the cotton industry under very deep tillage (VDT). With on-board-module-building, heavy cotton pickers (→35 Mg) introduction, it may happen that the subsoil compaction effect to extending from ~30 cm depth to ~100 cm (Bennett et al., 2016; Bennett et al., 2019). Through the study documentation of agronomic performance and soil structure getting better, this system can also be effective in recovering high lint yield via the mitigation of bulky traffic compaction impacts and enhanced root elongation. This system may be a profitable strategy however, the investigation of total costs is required to calculate the net profit when applied. This is an important practical consideration given that the cost of ripping is often perceived as one of the main barriers to the adoption of this technology. At the same time, RTF system is still in place in QLD and NSW Vertosols fields since a switch to CTF is very costly and needs infrastructure to establish. Consequently, deep tillage and VDT may offer a readily available solutions for mitigating compaction impacts on the productivity of the crops grown in these soils
- Deep tillage creates rapid and massive changes in soil physical properties such as lowering bulk density and strength, and increasing particle spacing. These changes may stabilize and continue if followed by the correct management or cease if such management processes are not continued. In evaluation research targeting deep tillage or comparison with other technologies, this aspect must be taken into account. In such projects, it is scientifically preferable to include cultivated crop/s and analysis their documented descriptive or production data as a reliable judgment when drawing conclusions. During this study and at Ag plot site, the percentage of ripping effects on crop performance were higher

after the first season, and this confirms that the subsoiling act has clearly came up after the stabilization of the soil condition. Monitoring deep ripping effects on the performance indicators of subsequent crops may be considered one of the most important practical recommendations. It is also preferable that the follow-up continues for at least two seasons or when the first crop is repeated.

- This research has also shown that applying the fertiliser rate was not economically feasible in soils experiencing compaction. Not adding fertilisers to these soils outweighed the fertilisation option in terms of gross and net profits. Not wasting money by purchasing costly fertilisers, as well as the costs of the application process, and mitigating compaction are the most important recommendations when the soil is compacted. With the increase in global N fertiliser prices, there is an urgent need to verify lower fertiliser rates than the ideal rate applied during this study to identify the economically feasible rate, in addition to the fact that the applied rate was not deduced from the practice of deep tillage
- After verifying procedural validity in heavy clay soils, it may be possible to apply Godwin and O'Dogherty' (G&O) modelling to estimate the tine pulling forces of existing rippers in dense soil conditions. As a result, growers could exploit the reported model to increase tillage operation efficiency, productivity and performance, as well as reduce energy losses and opportunities for soil compaction by choosing the appropriate tractor when linkage. Also, the model may play a role in decision-making by providing initial insights regarding the fundamental energy when switching to deep tillage as a surrogate technology to alleviate soil compaction. As it deals with tine geometry, the model is likely to support designers in testing and selecting the most efficient prototype before manufacturing after inspecting the draught power requirements. Designing and building a prototype as a ripper or injector and comparing its effect on soil properties and crop outcome with the existing designs may be considered the most important future recommendation to be addressed
- The APSIM modelling investigated in this study may be applied to identify potential increases and losses in crop yields in dense soils when executing deep tillage or aggravating soil compaction under distressing climatic conditions. Further, through its documented efficiency of long-term simulation, the

APSIM model can be one of the farm decision-making pillars for adopting deep tillage as a diagnostic strategy to alleviate soil compaction by comparing ripped soil productivity and resulting profits to corresponding scenarios

- Expansion of investigations scope to include more clay soils under both CTF and RTF systems, to optimise on farm-decisions regarding deep tillage adoption that may enhance the national and global agricultural production. Based on this research, it is expected that because of improvements in both yield quantity and soil quality, the agro-ecological performance would be significantly improved if deep tillage was more widely adopted
- This research provides essential cost and benefit analyses of ripping in the Darling Downs. Future studies should concentrate on analysing these costs and benefits at a regional level.

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APPENDICES

A. Field application of methodology

A.1 Ag plot site

A.1.1 (A) Machinery unit (JD 6115 R with Maschio FRESA B 205 rotary hoe) during cut, chop and mix of sorghum trash and residue, (B) Site after rotary-hoeing

A.1.2 (A) Machinery unit (NH T6.150 with Big Rig seeder) during wheat planting, (B) Nine rows of wheat planted by Big Rig seed drill

A.1.3 Bird netting and sprinkler irrigation system installation after wheat (Spitfire) planting

A.1.4 Videotape and scarecrow installation after seedlings emerge

A.1.5 (A) Digging the trench, (B) Adding and burying urea 46% N fertiliser, wheat season

A.1.6 Drying the biomass samples at 65˚C for 72 h, P12 (USQ lab)

A.2 Evanslea site

A.2.1 (A) Recording soil penetration resistance; (B) inserting hollow tube; and C: pulling soil bulk density tube (first time)

A.2.2 Elected locations with flags for sampling bulk density and penetrometer readings during sorghum season

A.2.3 Sorghum biomass collecting process

A.2.4 Harvesting collecting process: (A) Identifying three meters of the elected sorghum row, (B) Manual head cutting and packing in sand bags

B. Economic assessment

B.1 Cost of subsoiling

B.1.1 Detailed information on estimating total costs of owning and operating tractors and rippers during this study at both sites, and contractor rates

Symbol	Values	Ag plot - Season 2017				Evanslea - Season 2018				Units
		John Deere 6150M		Single Tine Ripper		John Deere 7920		Tilco-Eight Tine Ripper		
		Deep 1	Deep 2	Deep 1	Deep 2	Deep 1	Deep 2	Deep 1	Deep 2	
A	New price	120645	120645	1078	1078	160000	160000	28512	28512	AUD
B	Trade-in value	12065	12065	108	108	16000	16000	2851	2851	AUD
C	Age at trade-in	12	12	10	10	12	12	10	10	year
D	Yearly work	1000	1000	300	300	1000	1000	300	300	h/year
E	Interest rate	7	7	7	7	7	7	7	7	%
F	Insurance & housing rate	1	1	-	-	1	1	-	-	%
G	Field capacity	0.334±0.007	0.310±0.008	0.334±0.007	0.310±0.008	2.621±0.043	2.576±0.046	2.621±0.043	2.576±0.046	ha/h
H	Repair & maintenance factors	2	2	2	2	2	2	2	2	%
I	Labour wage rate	15	15	-	-	15	15	-	-	AUD/h
J	Labour adjustment factor	1.1	1.1	-	-	1.1	1.1	-	-	%
K	Diesel fuel consumption	5.51±0.118	6.69±0.173	-	-	9.95±0.301	18.02±1.828	-	-	L/h
L	Diesel price rate	1.19	1.19	-	-	1.265	1.265	-	-	AUD/L
M	Lubrication factor	15	15	-	-	15	15	-	-	%
N	Registration (RTA)	188.85	188.85	-	-	188.85	188.85	-	-	AUD/year
O	Average value = (A + B) / 2	66354.75	66354.75	592.9	592.9	88000	88000	15681.60	15681.60	AUD
Ownership (Fixed) Costs										

Symbol	Values	Ag plot - Season 2017				Evanslea - Season 2018				Units
		John Deere 6150M		**Single Tine Ripper**		**John Deere 7920**		**Tilco-Eight Tine Ripper**		
		Deep 1	**Deep 2**	**Deep 1**	**Deep 2**	**Deep 1**	**Deep 2**	**Deep 1**	**Deep 2**	
P	Depreciation = (A - B) / C	9048.38	9048.38	97.02	97.02	12000	12000	2566.08	2566.08	AUD/year
Q	Interest = O × E	4644.83	4644.83	41.50	41.50	6160	6160	1097.71	1097.71	AUD/year
R	Insurance & housing= O × F	663.55	663.55	-	-	880	880	-	-	AUD/year
S	Registration = N	188.85	188.85	-	-	188.85	188.85	-	-	AUD/year
Variable (Operating) Costs										
T	Repairs & maintenance = (A × H) / D	2.41	2.41	0.07	0.07	3.20	3.20	1.90	1.90	AUD/h
V	Labour = I × J	16.5	16.5	-	-	16.5	16.5	-	-	AUD/h
W	Diesel fuel = K × L	6.56 ±0.141	7.96±0.206	-	-	12.59±0.32	22.79±2.31	-	-	AUD/h
X	Lubrication = M × W	0.98±0.021	1.19±0.031	-	-	1.89±0.06	3.42±0.35	-	-	AUD/h
Total Ownership Costs										
Y	Per year = P + Q + R + S	14545.61	14545.61	138.52	138.52	19228.85	19228.85	3663.71	3663.71	AUD/year
Z	Per hour = Y / D	14.55	14.55	0.46	0.46	19.23	19.23	12.21	12.21	AUD/h
$A^{\times}$	Per hectare = Z / G	43.61±0.938	46.95±1.241	1.38±0.030	1.49±0.039	7.34±0.12	7.47±0.13	4.66±0.08	4.74±0.08	AUD/ha
Total Variable Costs										
$B^{\times}$	Per year = (T+V+W+X) × D	26456.32±162	28069.74±237	21.56	21.56	34179.61±438	45909.75±2659	570.24	570.24	AUD/year
$C^{\times}$	Per hour = T+V+W+X	26.46±0.162	28.07±0.237	0.07	0.07	34.18±0.44	45.91±2.66	1.90	1.90	AUD/h
$D^{\times}$	Per hectare = $C^{\times}$ / G	79.33±2.196	90.62±3.156	0.22±0.005	0.23±0.006	13.04±0.39	17.84±1.28	0.73±0.01	0.74±0.01	AUD/ha
Total Costs										
$E^{\times}$	Per year = Y+ $B^{\times}$	41001.92±162	42615.34±237	160.08	160.08	53408.46±438	65138.60±2659	4234.03	4234.03	AUD/year
$F^{\times}$	Per hour = Z + $C^{\times}$	41.00±0.16	42.62±0.24	0.53	0.53	53.41±0.44	65.14±2.66	14.11	14.11	AUD/h
$G^{\times}$	Per hectare = $A^{\times}$ + $D^{\times}$	122.95±3.134	137.57±4.397	1.60±0.034	1.72±0.046	20.38±0.51	25.30±1.40	5.39±0.09	5.48±0.1	AUD/ha

Symbol	Values	Ag plot - Season 2017				Evanslea - Season 2018				Units
		John Deere 6150M		**Single Tine Ripper**		**John Deere 7920**		**Tilco-Eight Tine Ripper**		
		Deep 1	**Deep 2**	**Deep 1**	**Deep 2**	**Deep 1**	**Deep 2**	**Deep 1**	**Deep 2**	
Total Machinery Unit Costs (Tractor + Ripper)		John Deere 6150M + Single Tine Ripper under:				John Deere 7920 + Tilco-Eight Tine Ripper under:				
		Deep 1		Deep 2		Deep 1		Deep 2		
H^x	Per year = $\sum E^x$	41162.01±162		42775.43±237		57642.49±438		69372.63±2659		AUD/year
I^x	Per hour = $\sum F^x$	41.54±0.162		43.15±0.237		67.52±0.438		79.25±2.66		AUD/h
J^x	Per hectare = $\sum G^x$	124.55 ±3.169		139.29±4.443		25.77±0.51		30.79±1.48		AUD/ha
Contractor Cost Values per hour		John Deere 6150M + Single Tine Ripper under:				John Deere 7920 + Tilco-Eight Tine Ripper under:				
		Deep 1		Deep 2		Deep 1		Deep 2		
K^x	Job sub-total = I^x	41.54±0.162		43.15±0.237		67.52±0.44		79.25±2.66		AUD/h
L^x	Contingency margin=5% × K^x	2.08±0.008		2.16±0.012		3.38±0.022		3.96±0.133		AUD/h
M^x	Profit margin = 20% × K^x	8.31±0.032		8.63±0.047		13.50±0.088		15.85±0.532		AUD/h
N^x	Margins sub-total = L^x + M^x	10.38±0.040		10.79±0.059		16.88±0.109		19.81±0.665		AUD/h
Contract Rate										
O^x	Per hour = K^x + N^x	51.92±0.202		53.94±0.296		84.40±0.547		99.07±3.324		AUD/h
P^x	Per hectare = O^x / G	155.68±3.961		174.11±5.553		32.21±0.748		38.48±1.853		AUD/ha

The new prices (A) for used tractors were obtained from the head office of Vanderfield Pty Ltd (the JD dealership), Toowoomba. The new prices (A) for used single and eight tines rippers were obtained from the FARM SUPPLIES and Tilco Ag Systems Company, Toowoomba. The QLD diesel prices rate were obtained from the diesel tables of Australian Institute of Petroleum (AIP) Bulletins. The tractor registration payments were obtained from the owner's receipts during the study year

B.2 Benefits of subsoiling clayey soil

B.2.1 Detailed information of Gross Income (GI), Total Variable Cost (TVC) and Gross Margin (GM) for the sorghum and wheat seasons, and total season 2017 at the Ag plot site

Ag plot - 2017 - Summer Sorghum - Elite Mr Buster

Symbol	Variable	0 kg N/ha			140 kg N/ha			Unit
		Cont.	D 1	D 2	Cont.	D 1	D 2	
A	Grain Yield	4.097	4.575	4.716	4.388	4.964	5.360	tonnes/ha
B	Selling Price	282.25	282.25	282.25	282.25	282.25	282.25	AUD/tonne
C	Gross Income=A×B	1156.4	1291.4	1331.2	1238.6	1401.0	1512.9	AUD/ha
D	Variable Costs	117.4	117.4	117.4	203.4	203.4	203.4	AUD/ha
E	Deep Ripping Cost	0	124.55	139.29	0	124.55	139.29	AUD/ha
F	Total Costs = D + E	117.4	241.9	256.7	203.4	327.9	342.6	AUD/ha
G	Gross Margin=C -F	1039.1	1049.5	1074.5	1035.3	1073.1	1170.3	AUD/ha

Detailed variable costs excluding deep ripping

Operations & materials applied	Application / Operation	Quantity		AUD per		Total AUD/ha	
		kg/ha	L/ha	kg	L	0 kg N/ha	140 kg N/ha
Elite Mr Buster seed	**1**	3		18		54	54
Sowing	**1**					10.39	10.39
Urea 46% N	**1**	304		0.28		0	84.86
Urea application**	**1**					0	1.1
Harvesting**	**1**					53	53
Total variable costs (AUD/ha)						117.4	203.4

Ag plot - 2017 - Winter Wheat - Spitfire

Symbol	Variable	0 kg N/ha			110 kg N/ha			Unit
		Cont.	D 1	D 2	Cont.	D 1	D 2	
A′	Grain Yield	1.613	1.803	2.083	1.828	2.115	2.419	tonnes/ha
B′	Selling Price	262	262	262	262	262	262	AUD/tonne
C′	Gross Income=A′×B′	422.7	472.4	545.7	479.0	554.2	633.7	AUD/ha
D′	Total Variable Costs	73.5	73.5	73.5	141.3	141.3	141.3	AUD/ha
E′	Gross Margin = C′- D′	349.2	398.9	472.2	337.7	412.9	492.4	AUD/ha

Detailed variable costs

Operations & materials applied	Application / Operation	Quantity		AUD per		Total AUD/ha	
		kg/ha	L/ha	kg	L	0 kg N/ha	110 kg N/ha
Spitfire seed	1	46		0.76		34.96	34.96
Sowing	1					12.5	12.5
Urea 46% N	1	239		0.28		0	66.75
Urea application**	1					0	1.1
Harvesting**	1					26	26
Total variable costs (AUD/ha)						73.5	141.3

Ag plot - 2017 Season

Benefits	Without Urea			With Urea			Unit
	Cont.	D 1	D 2	Cont.	D 1	D 2	
Gross Income = C + C′	1579	1763.7	1876.8	1717.4	1955.2	2146.6	AUD/ha
Gross Margin = G + E′	1388.1	1448.3	1546.7	1372.8	1486	1662.7	AUD/ha

** Although the harvest and applied urea were manual, the mechanical harvesting and fertiliser application costs were tabled, and so the results will be as much as possible real and similar to the farmers' agenda

B.2.2 Detailed information of gross income, total variable cost, and gross margin measuring of sorghum seasons 2018 at the Evanslea site

Evanslea - 2018 - Sorghum - Elite Mr Buster					
Symbol	**Variable**	**Control**	**Deep One**	**Deep Two**	**Unit**
A	Grain Yield	6.900	8.100	7.898	tonnes/ha
B	Selling Price	280	280	280	AUD/tonne
C	Gross Income = A × B	1932	2267.9	2211.4	AUD/ha
D	Variable Costs	416.7	416.7	416.7	AUD/ha
E	Deep Ripping Cost	0	25.77	30.79	AUD/ha
F	Total Costs = D + E	416.7	442.47	447.49	AUD/ha
G	Gross Margin = C - F	1515.3	1825.5	1763.9	AUD/ha

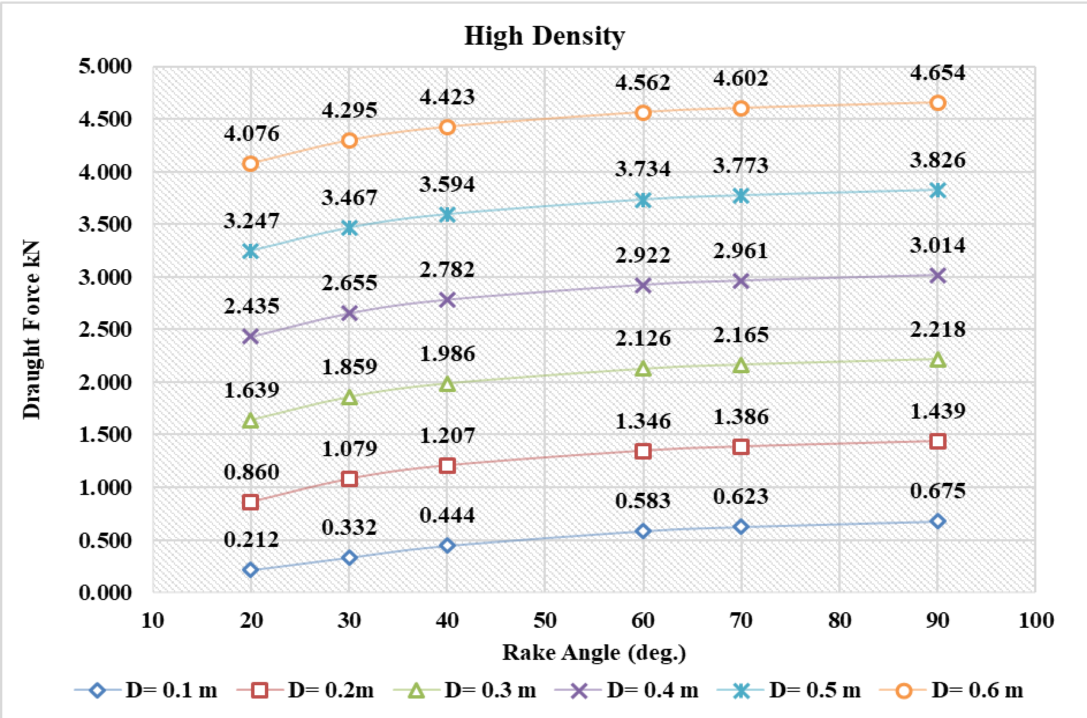
Detailed variable costs excluding deep ripping						
Operations & materials applied	**Application / Operation**	**Quantity**		**AUD per**		**Total AUD/ha**
		kg/ha	**L/ha**	**kg**	**L**	
Herbicide: Glyphosate	**2**		1.2		6.45	15.48
Herbicide: Amicide Advance	**1**		0.4		16.2	6.48
Herbicides sprayer	**2**					4
Anhydrous ammonia	**1**	100			0.67	67
Anhydrous application	**1**					13.57
Elite Mr Buster seed	**1**	2.6		20		52
Yara Flowphos 13Z	**1**		15		2	30
Planter (seed)	**1**					13.57
Urea: Farm Gate	**1**	150		0.55		82.5
Urea spreader	**1**					1.1
Herbicide: Atrazine	**1**		3.5		8.6	30
Herbicides sprayer	**1**					2
Insecticide: Vivus Max	**1**		0.15		62.4	9
Aerial spray	**1**					14
Harvesting	**1**					53
Other (levy, drying, insurance, consultant... etc.)						23
Total						416.7

C. G&O single tine model sensitivity

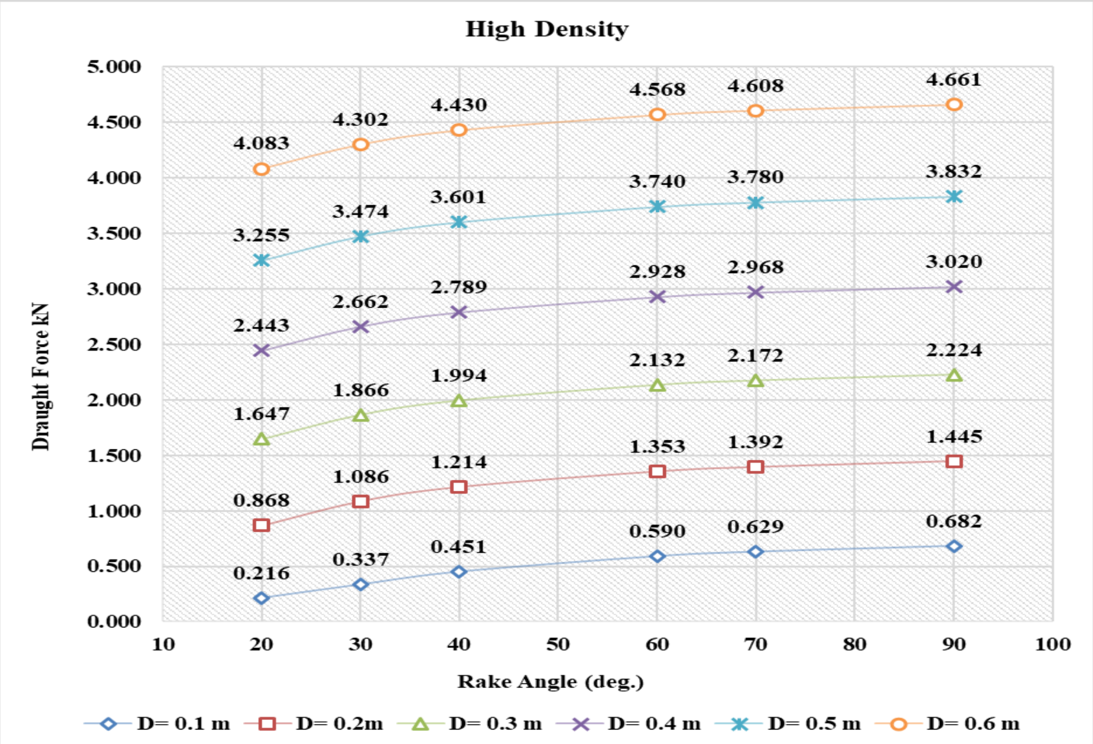
Case	1				2				3				Unit
Sub-case	1	2	3	4	1	2	3	4	1	2	3	4	
Bulk unit weight	15	15	15	15	12.5	12.5	12.5	12.5	10	10	10	10	kN/m^3
Int. friction angle	10	10	10	10	10	10	10	10	10	10	10	10	Deg.
Cohesion	16	16	16	16	16	16	16	16	16	16	16	16	kN/m^2
Ext. friction angle	10	10	10	10	10	10	10	10	10	10	10	10	Deg.
Adhesion	0	0	0	0	0	0	0	0	0	0	0	0	kN/m^2
Surcharge	0	0	0	0	0	0	0	0	0	0	0	0	kN/m^2
Tine speed	0.56	1.11	1.67	2.22	0.56	1.11	1.67	2.22	0.56	1.11	1.67	2.22	m/s
Tine width	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	m

C.1 Case 1: High bulk unit weight

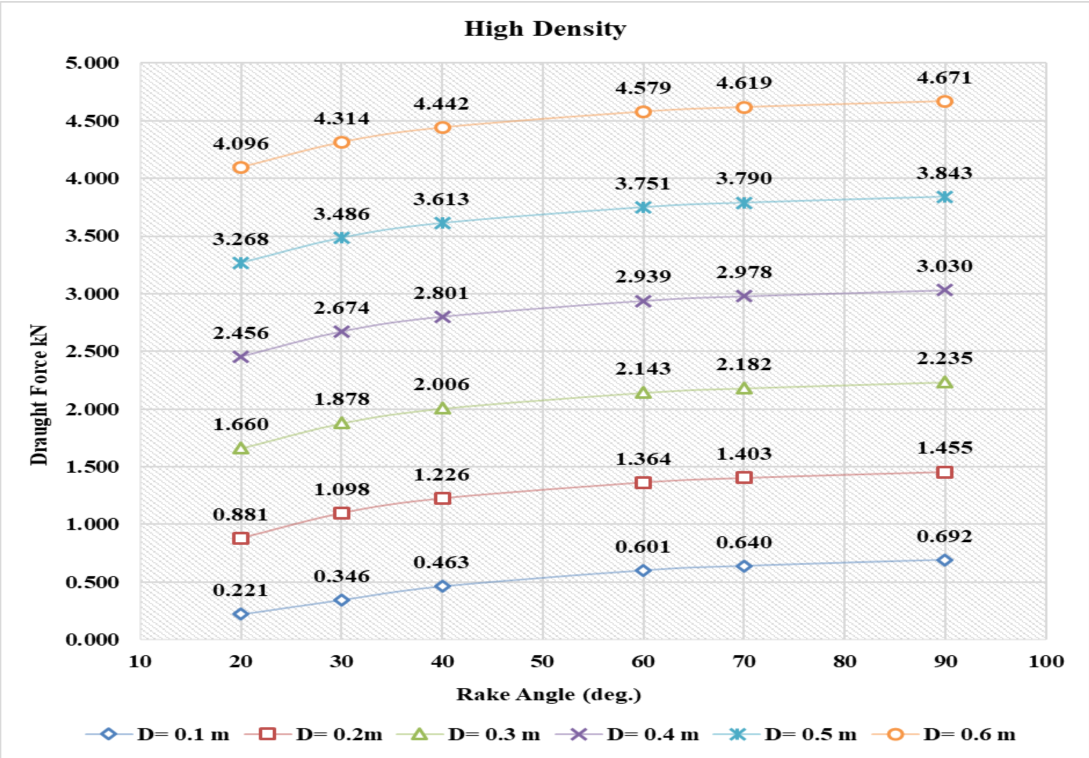
C.1.1 Sub-case 1



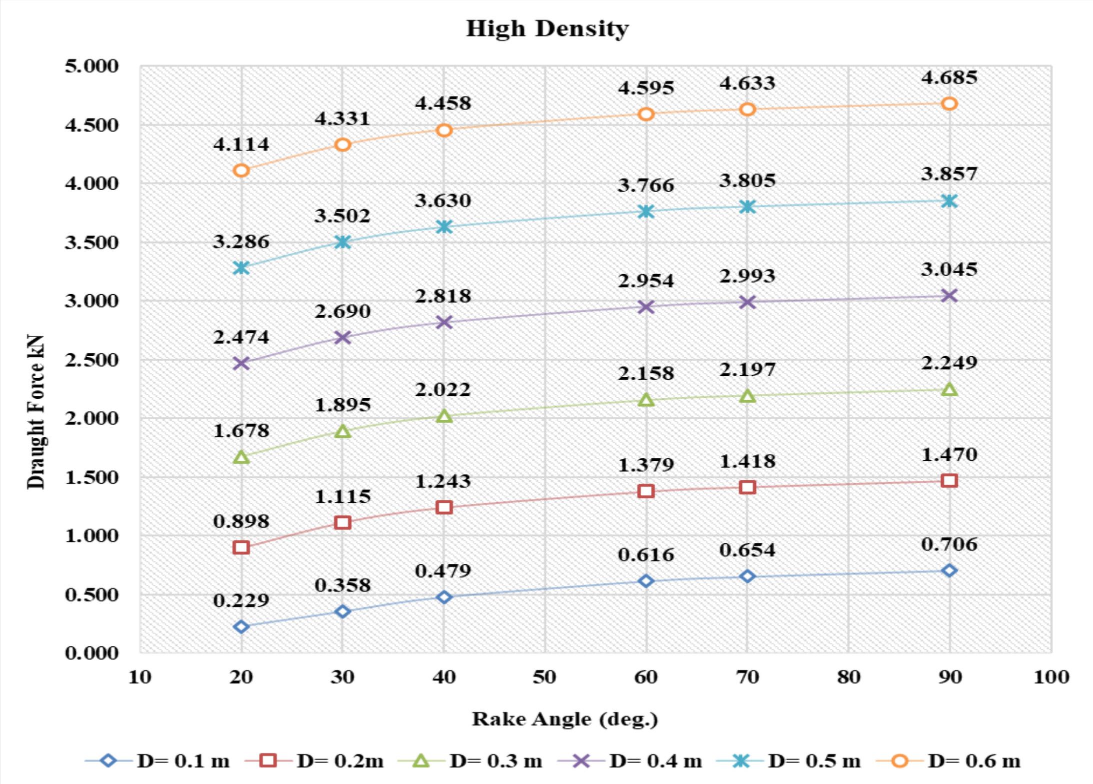
C.1.2 Sub-case 2



C.1.3 Sub-case 3

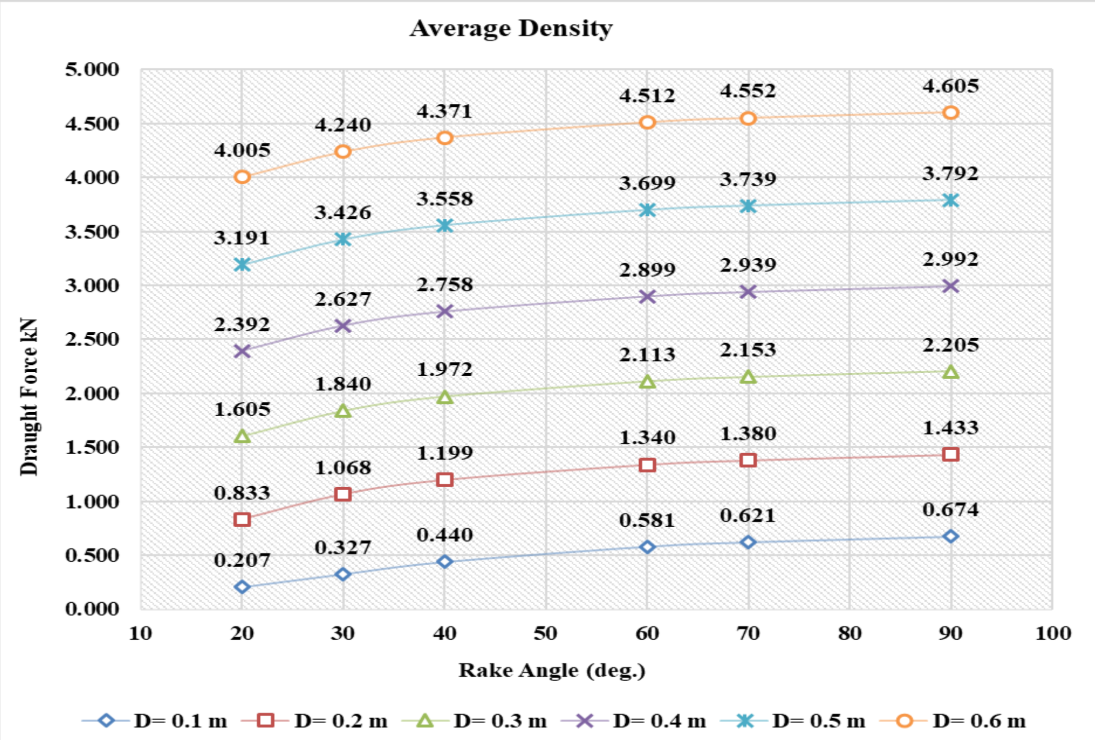


C.1.4 Sub-case 4

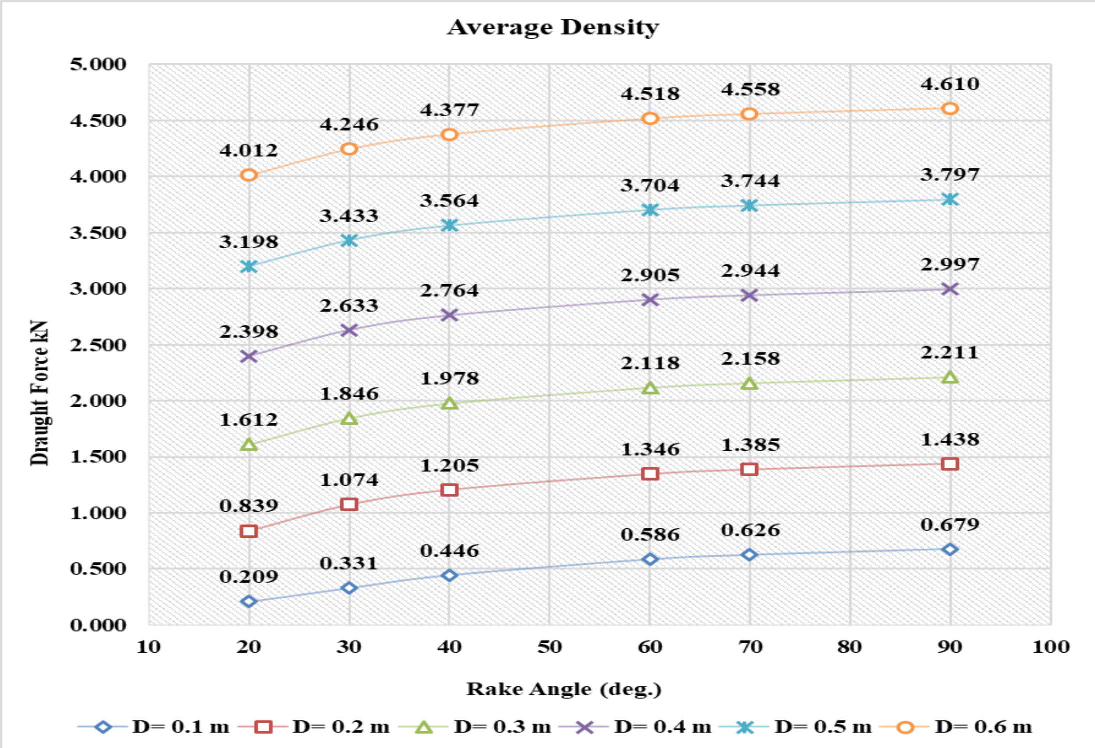


C.2 Case 2: Moderate bulk unit weight

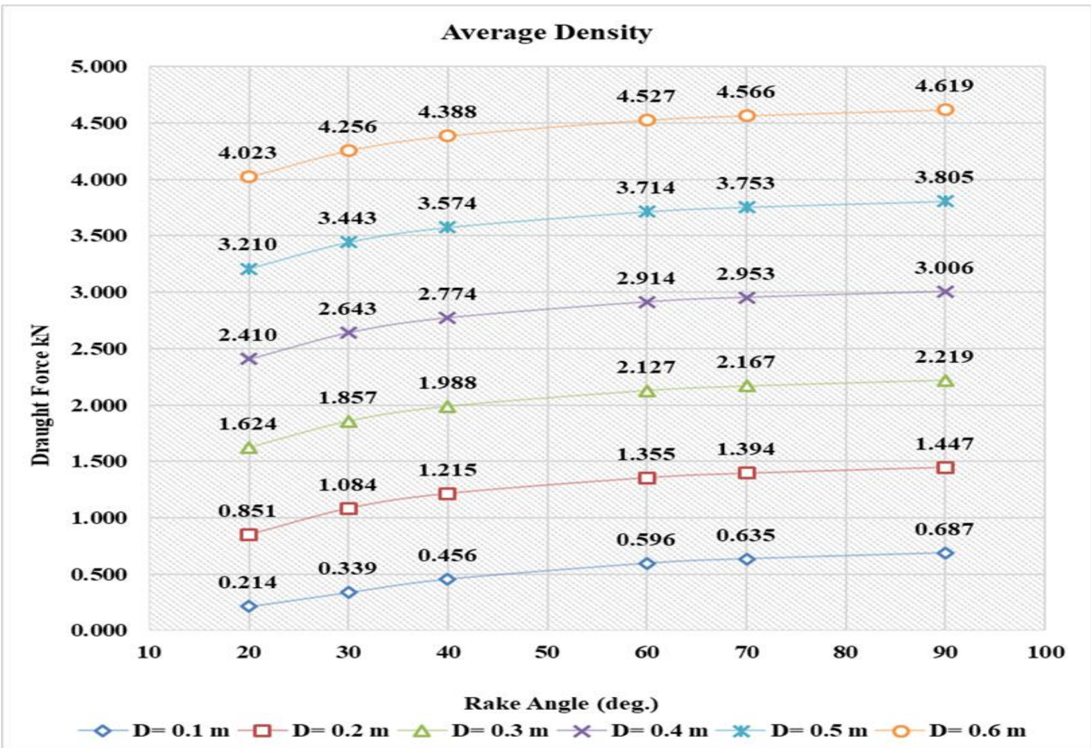
C.2.1 Sub-case 1



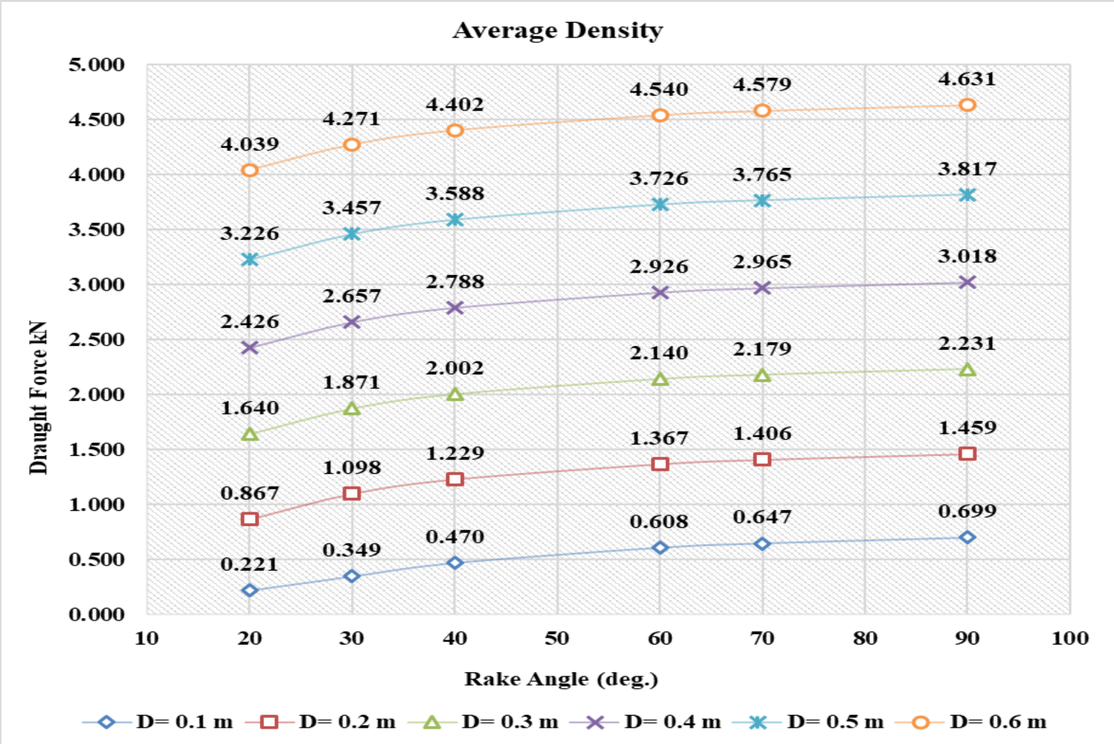
C.2.2 Sub-case 2



C.2.3 Sub-case 3

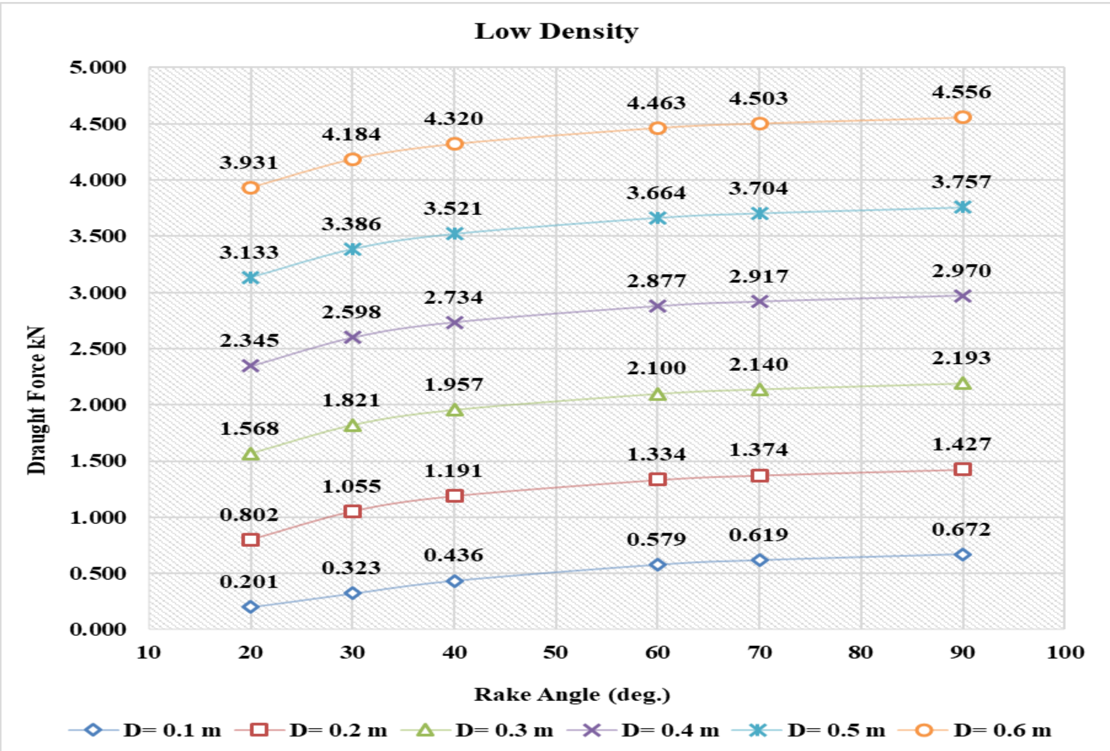


C.2.4 Sub-case 4

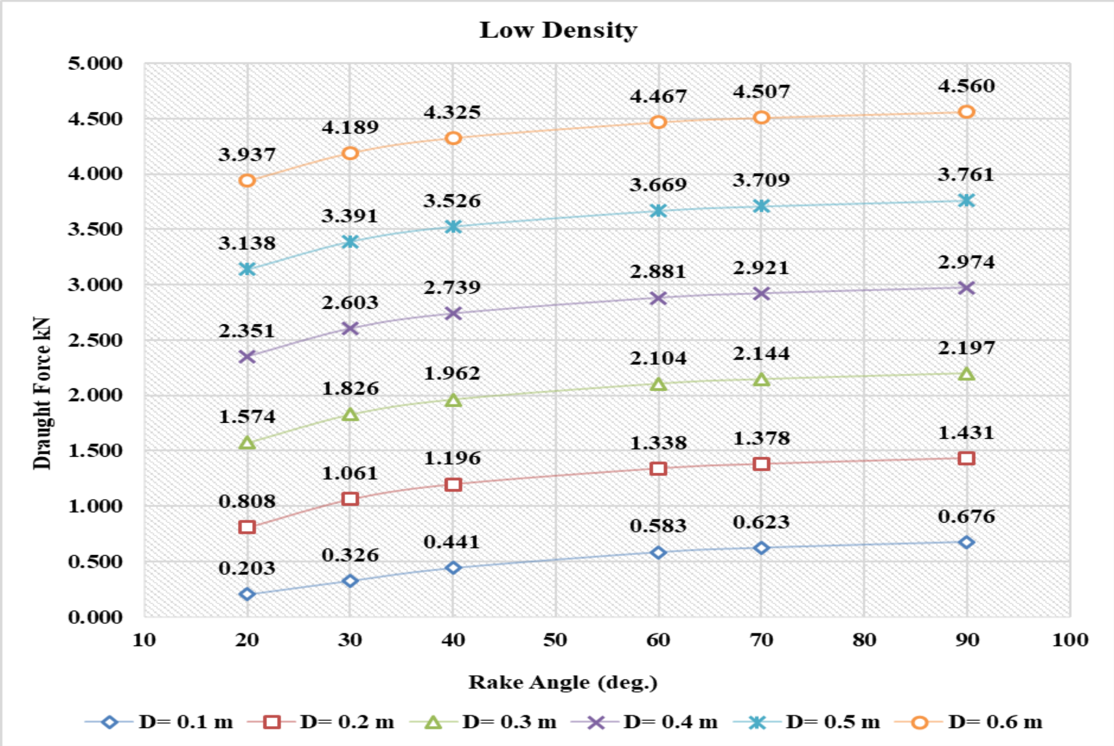


C.3 Case three: Low bulk unit weight

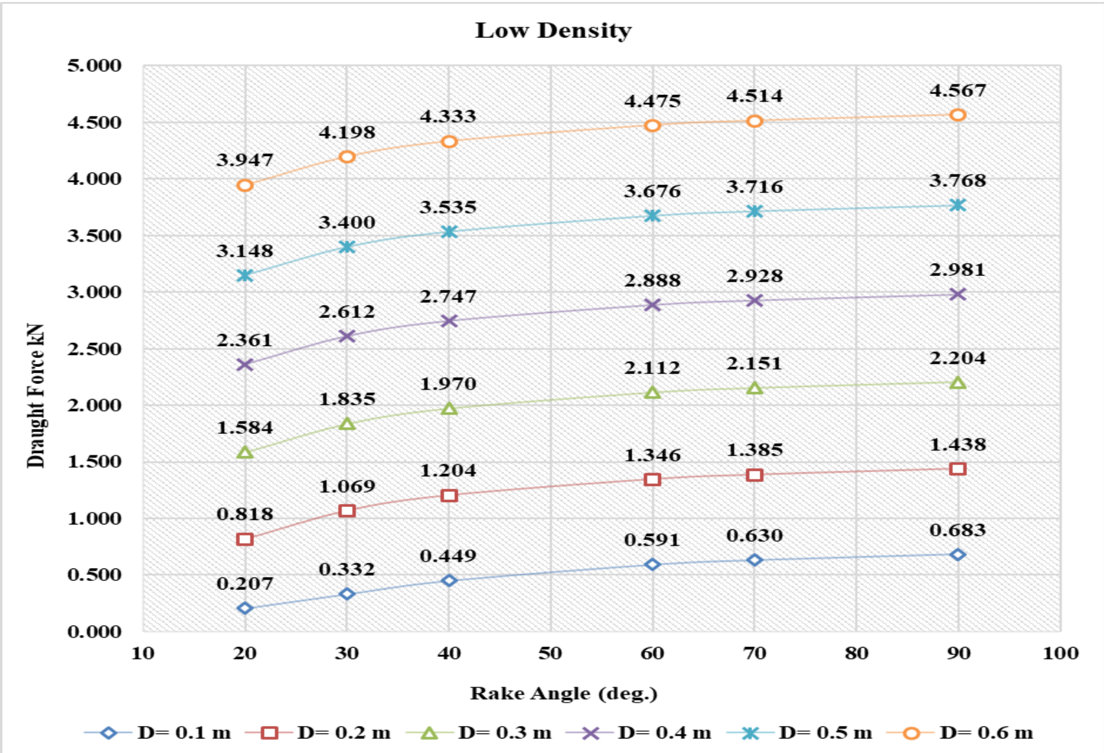
C.3.1 Sub-case 1



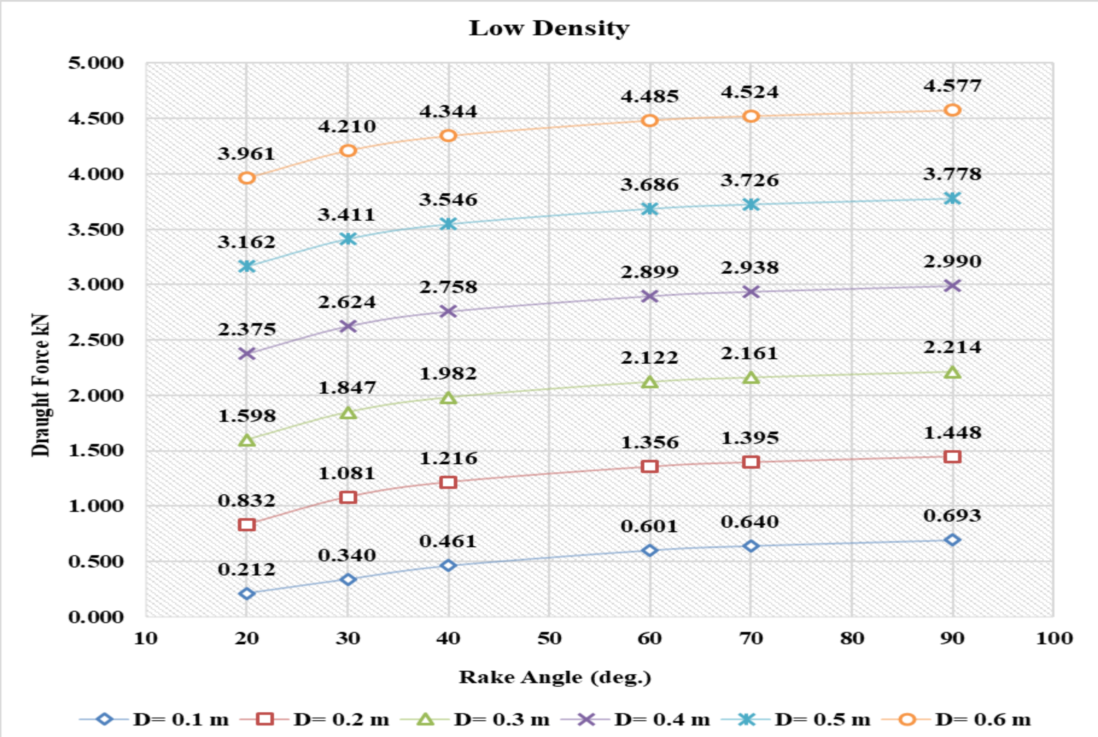
C.3.2 Sub-case 2



C.3.3 Sub-case 3



C.3.4 Sub-case 4



D. Crop performance modelling work

D.1 Soil and water properties

D.1.1 Soil properties used in the simulations for (C), (D1) and (D2) conditions for a Red Ferrosol soil at Ag plot site: ρ ,bulk density, LL, lower limit, DUL, drained upper limit, SAT, saturation water content, KS and saturated hydraulic conductivity. Note: data with standard deviation (Std.) are measured data whereas the derived data are without Std.

Control (C) / Depth (cm)	**ρ (g/cm³)**		**Total porosity (%)**		**Plant LL (m³/m³)**		**DUL (m³/m³)**		**SAT (m³/m³)**		**K_S (mm/day)**
	Sorghum	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	
0-15	1.304±0.049	1.312±0.069	51±0.026	51±0.037	0.193±0.007	0.163±0.008	0.259± 0.009	0.254±0.013	0.478±0.026	0.475±0.037	52±2.370
15-30	1.429±0.027	1.437±0.012	46±0.014	46±0.006	0.219±0.004	0.213±0.002	0.289± 0.005	0.344±0.003	0.431±0.014	0.428±0.006	24±0.924
30-60	1.419±0.006	1.430±0.078	46±0.003	46±0.042	0.280±0.046	0.241±0.013	0.399± 0.066	0.401±0.022	0.435±0.003	0.430±0.042	9±0.874
60-90	1.434±0.064	1.439±0.06	46±0.034	46±0.032	0.275±0.009	0.283±0.012	0.392± 0.012	0.398±0.017	0.429±0.034	0.427±0.032	25
90-120	1.400	1.400	47	47	0.290	0.334	0.392	0.398	0.442	0.442	25
120-150	1.400	1.400	47	47	0.280	0.339	0.364	0.365	0.442	0.442	25
150-180	1.400	1.400	47	47	0.291	0.344	0.350	0.351	0.442	0.442	25
D1 / Depth (cm)	**ρ (g/cm³)**		**Total porosity (%)**		**Plant LL (m³/m³)**		**DUL (m³/m³)**		**SAT (m³/m³)**		**K_S (mm/day)**
	Sorghum	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	
0-15	1.153±0.098	1.209±0.079	57±0.052	54±0.042	0.187±0.016	0.156±0.010	0.221± 0.019	0.242±0.016	0.535±0.052	0.514±0.042	1033±33.022
15-30	1.280±0.039	1.324±0.015	52±0.021	50±0.008	0.246±0.007	0.226±0.002	0.300± 0.009	0.365±0.004	0.487±0.021	0.471±0.008	460±39.171
30-60	1.398±0.047	1.391±0.063	47±0.025	48±0.034	0.302±0.010	0.238±0.011	0.378± 0.013	0.396±0.018	0.442±0.025	0.445±0.034	86±13.948
60-90	1.425±0.035	1.371±0.013	46±0.019	48±0.007	0.324±0.008	0.277±0.003	0.410± 0.010	0.401±0.004	0.432±0.019	0.453±0.007	50
90-120	1.390	1.390	48	48	0.307	0.310	0.389	0.392	0.445	0.445	50
120-150	1.380	1.280	48	48	0.328	0.341	0.400	0.379	0.449	0.449	25
150-180	1.370	1.370	48	48	0.303	0.356	0.370	0.367	0.453	0.453	25

D2 Depth (cm)	ρ (g/cm^3)		Total porosity (%)		Plant LL (m^3/m^3)		DUL (m^3/m^3)		SAT (m^3/m^3)		K_S (mm/day)
	Sorghum	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	**Sorghum**	**Wheat**	
0-15	1.145±0.137	1.179±0.066	57±0.073	55±0.035	0.180±0.022	0.152±0.008	0.224± 0.027	0.236±0.013	0.538±0.073	0.525±0.035	1049±49.914
15-30	1.201±0.110	1.280±0.029	55±0.059	52±0.015	0.217±0.020	0.228±0.005	0.279± 0.025	0.368±0.008	0.517±0.059	0.487±0.015	483±16.324
30-60	1.408±0.046	1.390±0.047	47±0.025	47±0.025	0.293±0.009	0.250±0.008	0.371± 0.012	0.416±0.014	0.439±0.025	0.445±0.025	107±17.219
60-90	1.416±0.044	1.369±0.007	47±0.023	48±0.004	0.314±0.009	0.292±0.001	0.403± 0.012	0.417±0.002	0.436±0.023	0.453±0.004	50
90-120	1.390	1.390	48	48	0.307	0.332	0.389	0.415	0.445	0.445	50
120-150	1.380	1.380	48	48	0.320	0.361	0.400	0.402	0.449	0.449	25
150-180	1.380	1.380	48	48	0.306	0.377	0.373	0.392	0.449	0.449	25

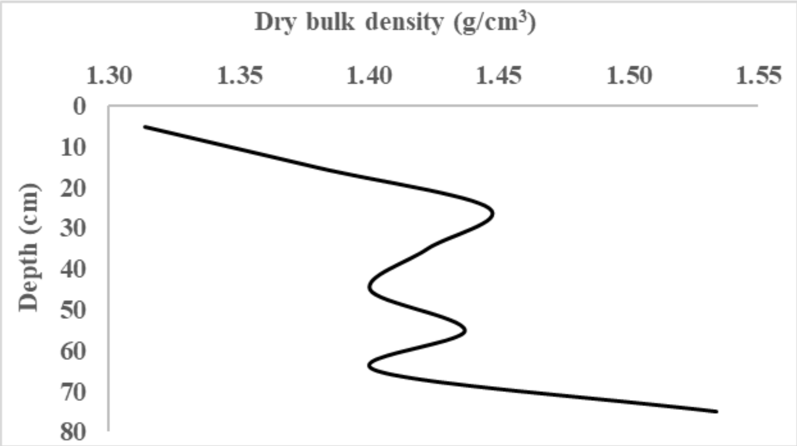
D.1.2 Soil properties used in the simulations for (C), (D1) and (D2) farming conditions for a black Vertosol soil during sorghum season at Evanslea site, where: ρ, bulk density; LL, lower limit, DUL, drained upper limit, SAT, saturation water content, KS and saturated hydraulic conductivity. Note: data with standard deviation (Std) are the measured data whereas the derived data are without Std.

Control (C) = No Ripping						
Depth (cm)	**ρ (g/cm^3)**	**Total porosity (%)**	**Plant LL (m^3/m^3)**	**DUL (m^3/m^3)**	**SAT (m^3/m^3)**	**K_S (mm/day)**
0-15	1.022±0.030	61±0.011	0.235± 0.007	0.470± 0.014	0.584±0.011	64±4.01
15-30	1.053±0.024	60±0.009	0.246± 0.006	0.491± 0.011	0.573±0.009	35±2.85
30-60	1.109±0.081	58±0.031	0.256± 0.019	0.512± 0.037	0.551±0.031	11±1.87
60-90	1.136±0.089	57±0.034	0.318± 0.025	0.522± 0.041	0.541±0.034	25
90-120	1.090	59	0.370	0.500	0.559	25
120-150	1.080	59	0.418	0.480	0.562	25
150-180	1.040	61	0.456	0.470	0.578	25
Deep Ripping one (D1)						
Depth (cm)	**ρ (g/cm^3)**	**Total porosity (%)**	**Plant LL (m^3/m^3)**	**DUL (m^3/m^3)**	**SAT (m^3/m^3)**	**K_S (mm/day)**
0-15	0.932±0.063	65±0.024	0.180± 0.012	0.450± 0.030	0.618±0.024	1134±14.65
15-30	0.981±0.042	63±0.016	0.249± 0.011	0.497± 0.021	0.600±0.016	560±5.74
30-60	1.002±0.070	62±0.026	0.242± 0.017	0.493± 0.034	0.592±0.026	103±2.84
60-90	1.141±0.050	57±0.019	0.326± 0.014	0.534± 0.023	0.539±0.019	50
90-120	1.120	58	0.418	0.522	0.547	50
120-150	1.150	57	0.408	0.480	0.536	25
150-180	1.190	55	0.467	0.467	0.521	25
Deep Ripping one (D1)						
Depth (cm)	**ρ (g/cm^3)**	**Total porosity (%)**	**Plant LL (m^3/m^3)**	**DUL (m^3/m^3)**	**SAT (m^3/m^3)**	**K_S (mm/day)**
0-15	0.892±0.063	66±0.024	0.178± 0.013	0.446± 0.032	0.633±0.024	1217±16.15
15-30	0.948±0.055	64±0.021	0.244± 0.014	0.488± 0.028	0.612±0.021	571±6.42
30-60	0.982±0.041	63±0.015	0.244± 0.010	0.488± 0.020	0.599±0.015	131±1.58
60-90	1.083±0.028	59±0.011	0.324± 0.009	0.531± 0.014	0.561±0.011	50
90-120	1.120	58	0.418	0.522	0.547	50
120-150	1.150	57	0.418	0.492	0.536	25
150-180	1.190	55	0.467	0482	0.521	25

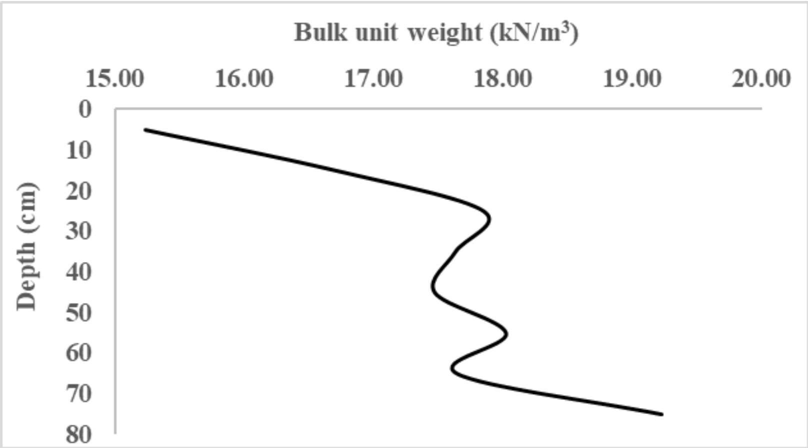
E. G&O single tine model validating

E.1 Physical properties of the experiment field soil - Ag plot

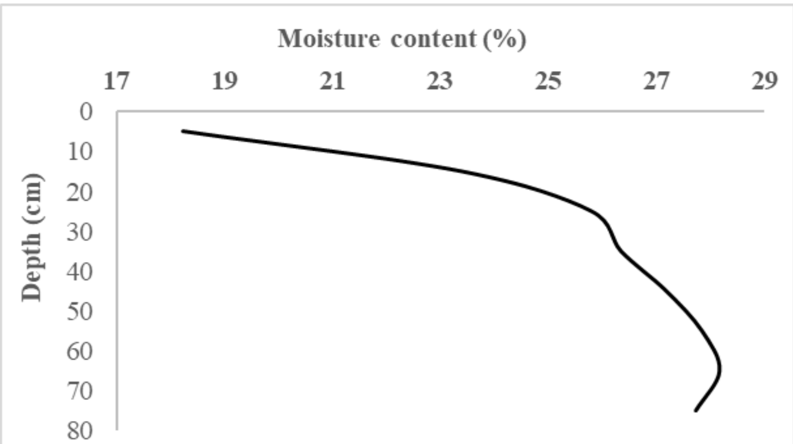
E.1.1 Dry bulk density



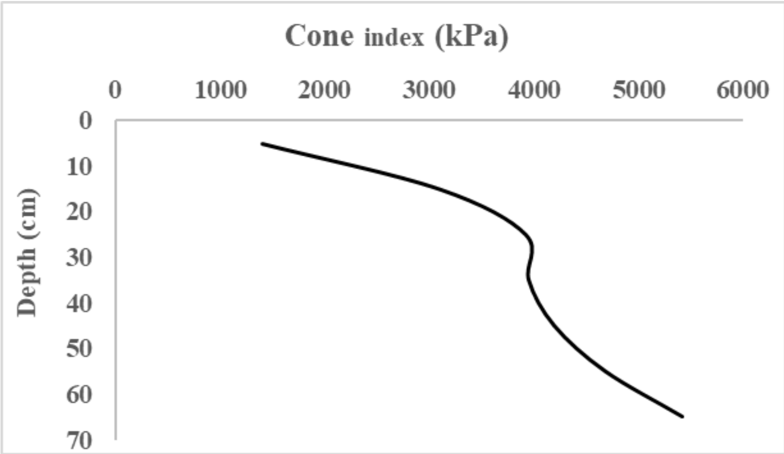
E.1.2 Bulk unit weight



E.1.3 Moisture content

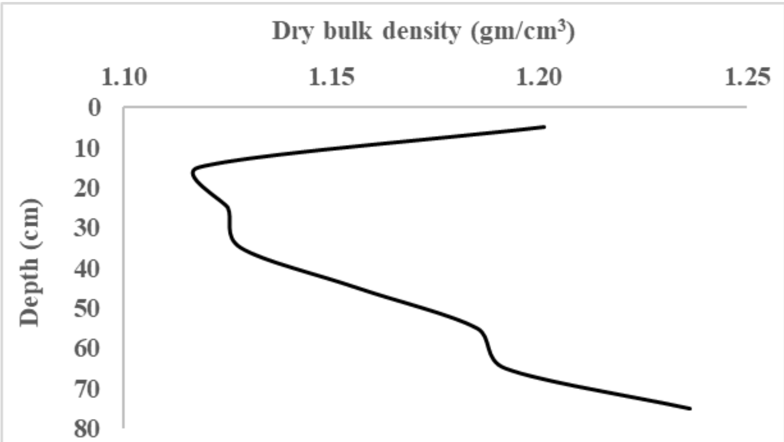


E.1.4 Cone index

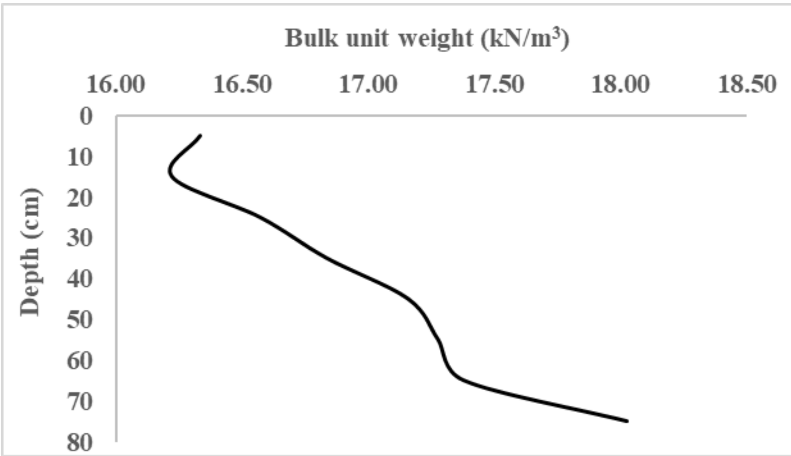


E.2 Physical properties of the experiment field soil - Evanslea site

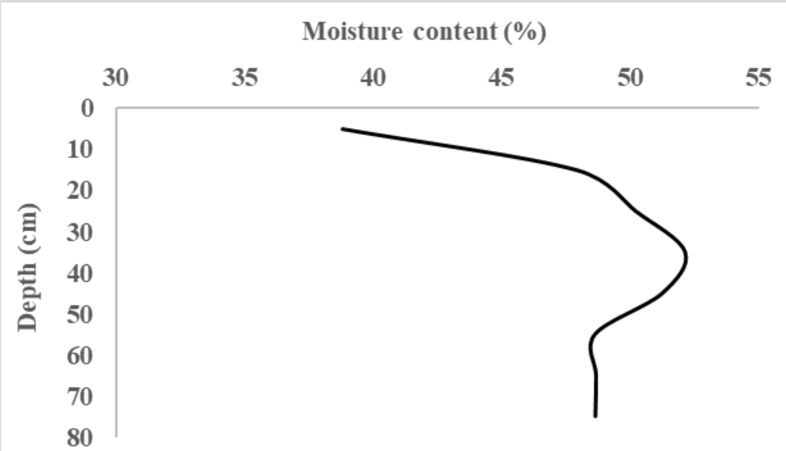
E.2.1 Dry bulk density



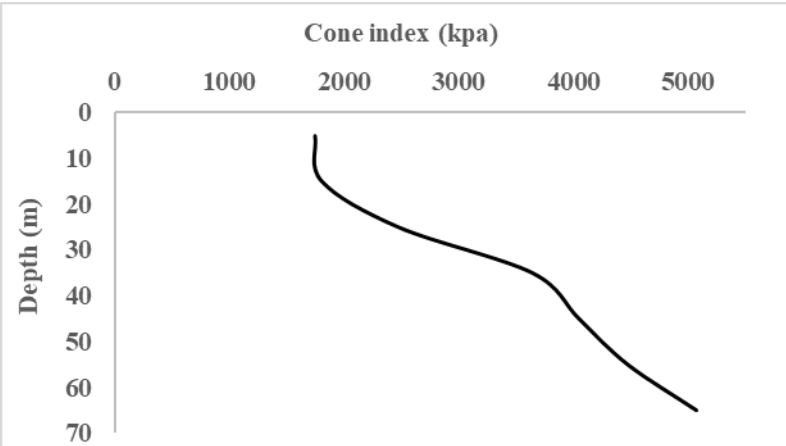
E.2.2 Bulk unit weight



E.2.3 Moisture content



E.2.4 Cone index



E.3 Inputs and outputs of G&O single tine model - Ag plot site

E.3.1 First practical depth

SINGLE TINE FORCES

This sheet calculates the draught and vertical forces acting on a single tine working in soil.

General Help | Explain Model | Supporting References | Add Calculation Rows

NOTES/DESCRIPTION	SOIL PARAMETERS					TINE PARAMETERS					DRAUGHT FORCE
	density	cohesion	internal friction angle	surcharge	interface friction angle	depth	width	rake angle	velocity	rupture distance ratio	
	γ	c	ϕ	q	δ	d	w	α	v	m	D
	kN/m^3	kN/m^2	deg	kN/m^2	deg	m	m	deg	m/s		kN
Notes	Enter values in rows below:									Values rightwards of here are calcu	
Ag -plot	17.84	32.48	36.84	0	23.2	0.05	0.095	35	0.76	2.21	0.44
USQ	17.84	32.48	36.84	0	23.2	0.1	0.095	35	0.76	2.21	1.48
Ripping Depth= 0.25 m	17.84	32.48	36.84	0	23.2	0.15	0.095	35	0.76	2.21	2.94
Adhesion= 18.5 kN/m2	17.84	32.48	36.84	0	23.2	0.2	0.095	35	0.76	2.21	4.93
	17.84	32.48	36.84	0	23.2	0.25	0.095	35	0.76	2.21	7.48
	17.84	32.48	36.84	0	23.2	0.3	0.095	35	0.76	2.21	10.63

E.3.2 Second practical depth

SINGLE TINE FORCES

This sheet calculates the draught and vertical forces acting on a single tine working in soil.

General Help | Explain Model | Supporting References | Add Calculation Rows

NOTES/DESCRIPTION	SOIL PARAMETERS					TINE PARAMETERS					DRAUGHT FORCE
	density	cohesion	internal friction angle	surcharge	interface friction angle	depth	width	rake angle	velocity	rupture distance ratio	
	γ	c	ϕ	q	δ	d	w	α	v	m	D
	kN/m^3	kN/m^2	deg	kN/m^2	deg	m	m	deg	m/s		kN
Notes	Enter values in rows below:									Values rightwards of here are calcu	
Ag -plot	18	33.63	36.37	0	22.32	0.1	0.095	35	0.67	2.21	1.31
USQ	18	33.63	36.37	0	22.32	0.2	0.095	35	0.67	2.21	4.85
Ripping Depth= 0.6 m	18	33.63	36.37	0	22.32	0.3	0.095	35	0.67	2.21	10.46
Adhesion = 18.11 kN/m2	18	33.63	36.37	0	22.32	0.4	0.095	35	0.67	2.21	18.55
	18	33.63	36.37	0	22.32	0.5	0.095	35	0.67	2.21	29.40
	18	33.63	36.37	0	22.32	0.6	0.095	35	0.67	2.21	43.28

E.4 Inputs and outputs of G&O single tine model - Evanslea site

E.4.1 First practical depth

SINGLE TINE FORCES

This sheet calculates the draught and vertical forces acting on a single tine working in soil.

General Help | Explain Model | Supporting References | Add Calculation Rows

NOTES/DESCRIPTION	SOIL PARAMETERS					TINE PARAMETERS					DRAUGHT FORCE
	density	cohesion	internal friction angle	surcharge	interface friction angle	depth	width	rake angle	velocity	rupture distance ratio	
	γ	c	φ	q	δ	d	w	α	v	m	D
	kN/m^3	kN/m^2	deg	kN/m^2	deg	m	m	deg	m/s		kN
Notes	Enter values in rows below:									Values rightwards of here are calcu	
Evanslea	16.38	60.51	21.35	0	17.29	0.05	0.095	47	0.73	1.95	0.95
Andrew Field	16.38	60.51	21.35	0	17.29	0.1	0.095	47	0.73	1.95	2.82
Ripping Depth= 0.3 m	16.38	60.51	21.35	0	17.29	0.15	0.095	47	0.73	1.95	5.60
Adhesion = 3.44 kN/m2	16.38	60.51	21.35	0	17.29	0.2	0.095	47	0.73	1.95	9.32
	16.38	60.51	21.35	0	17.29	0.25	0.095	47	0.73	1.95	14.00
	16.38	60.51	21.35	0	17.29	0.3	0.095	47	0.73	1.95	19.65

E.4.2 Second practical depth

SINGLE TINE FORCES

This sheet calculates the draught and vertical forces acting on a single tine working in soil.

General Help | Explain Model | Supporting References | Add Calculation Rows

NOTES/DESCRIPTION	SOIL PARAMETERS					TINE PARAMETERS					DRAUGHT FORCE
	density	cohesion	internal friction angle	surcharge	interface friction angle	depth	width	rake angle	velocity	rupture distance ratio	
	γ	c	φ	q	δ	d	w	α	v	m	D
	kN/m^3	kN/m^2	deg	kN/m^2	deg	m	m	deg	m/s		kN
Notes	Enter values in rows below:									Values rightwards of here are calcu	
Evanslea	16.63	58.29	20.53	0	16.51	0.1	0.095	45	0.72	1.98	2.50
Andrew Field	16.63	58.29	20.53	0	16.51	0.2	0.095	45	0.72	1.98	8.34
Ripping Depth= 0.5 m	16.63	58.29	20.53	0	16.51	0.3	0.095	45	0.72	1.98	17.63
Adhesion =2.42 kN/m2	16.63	58.29	20.53	0	16.51	0.4	0.095	45	0.72	1.98	29.43
	16.63	58.29	20.53	0	16.51	0.5	0.095	45	0.72	1.98	41.41
	16.63	58.29	20.53	0	16.51	0.6	0.095	45	0.72	1.98	53.47

E.5 Trilab tests results of Felton Black Vertosol samples

Trilab
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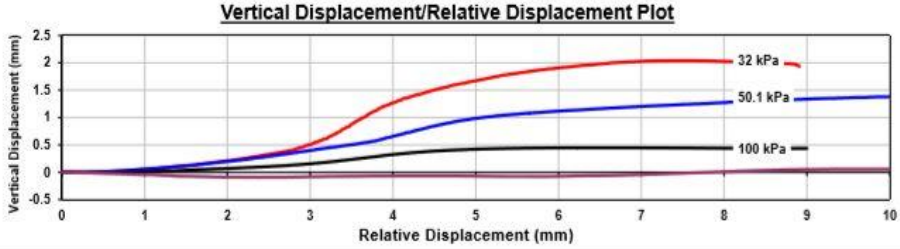
DIRECT SHEAR TEST REPORT

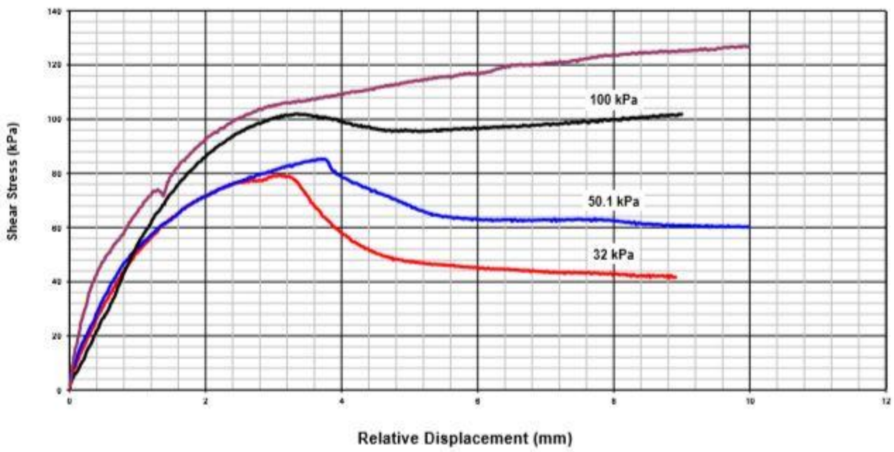
Test Method: AS 1289.6.2.2 / KH2 based on K.H. Head Vol. 2

Client	Dio Antille	**Report No.**	18030849- DS
		Workorder No	0003998
Address	University of Southern Queensland West St Toowoomba 4350	**Test Date**	5/04/2018
		Report Date	18/04/2018
Project	1006280		
Client ID	Vertisol	**Depth (m)**	Not Supplied
Description	SANDY CLAY - brown	**Sample Type**	Four Individual Soil Specimens - Remoulded as requested by the client.

Vertical Displacement/Relative Displacement Plot



Shear Stress/Displacement Plot



Notes/Remarks:

Note: Area correction based on square sample equation.

Graph not to scale

Sample/s supplied by the client

Page 1 of 4 REP07301

Accredited for compliance with ISO/IEC 17025 - Testing.
The results of the tests, calibrations, and/or measurements included in this document are traceable to Australian/National Standards.

Authorised Signatory

C. Channon

NATA

Tested at Trilab Brisbane Laboratory

Laboratory No. 9926

E.5.1 Cohesion and the internal friction angle

Trilab
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Queens Park
WA 6107
Ph: +61 8 9258 8323

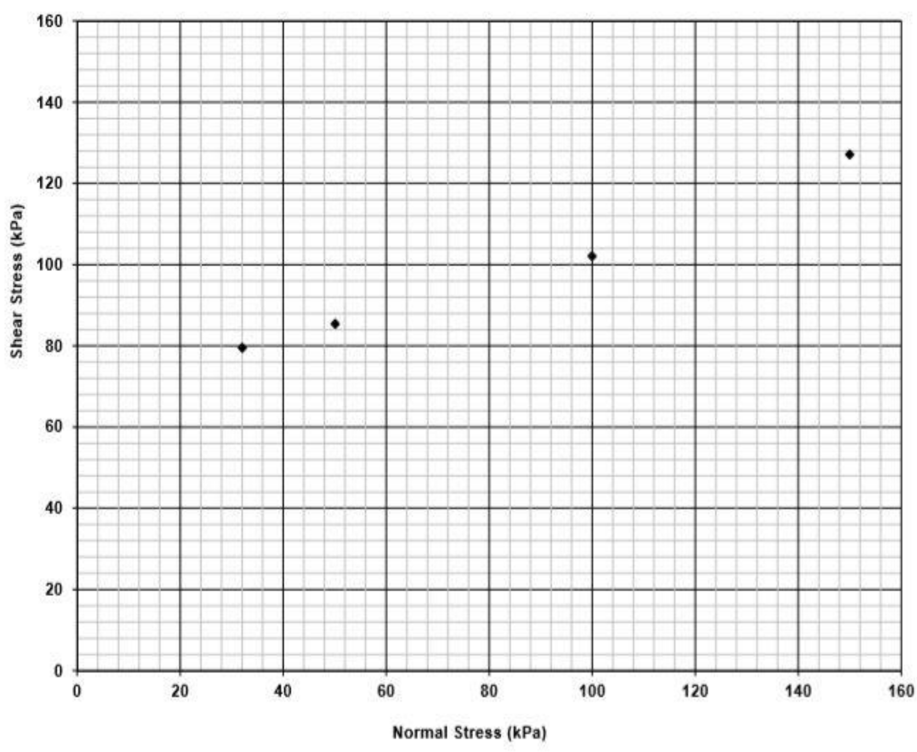
DIRECT SHEAR TEST REPORT

Test Method: AS 1289.6.2.2 / KH2 based on K.H. Head Vol. 2

Client	Dio Antille	**Report No.**	18030849- DS

Failure Criteria	**Peak**

Peak - Normal Stress vs Shear Stress



Shear Angle (°)	**21.8**	**Cohesion (kPa)**	**65.3**	**R^2**	**0.994**
Specimen Condition	As Received	Normal Stress (kPa)		Corrected Shear Stress (kPa)	
Specimen Dimensions (mm)	100*100	Stage 1	32.0	79.5	
Rate of Strain (mm/min)	0.008	Stage 2	50.1	85.4	
Initial Moisture Content (%)	39.9	Stage 3	100.0	102.0	
Initial Wet Density(t/m^3)	1.40	Stage 4	150.0	127.1	

Notes/Remarks:

Note: Area correction based on square sample equation.

Graph not to scale Sample/s supplied by the client Page 3 of 4 REP07301

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Authorised Signatory

C. Channon

NATA

Laboratory No. 9926

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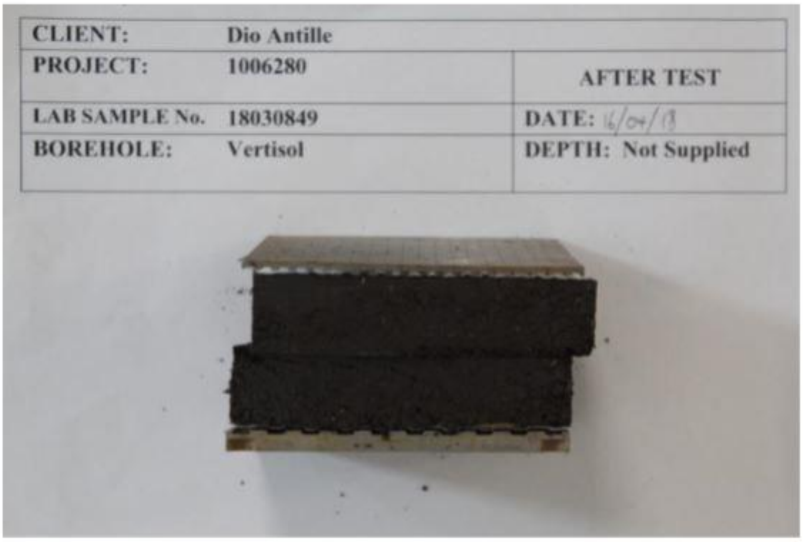
DIRECT SHEAR TEST REPORT

Test Method: AS 1289.6.2.2 / KH2 based on K.H. Head Vol. 2

Client	Dio Antille	**Report No.**	18030849- DS



Notes/Remarks:

Photo not to scale

Sample/s supplied by the client

Page 4 of 4 REP07301

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C. Channon

Laboratory No. 9926

E.5.2 Adhesion and the external friction angle

Trilab
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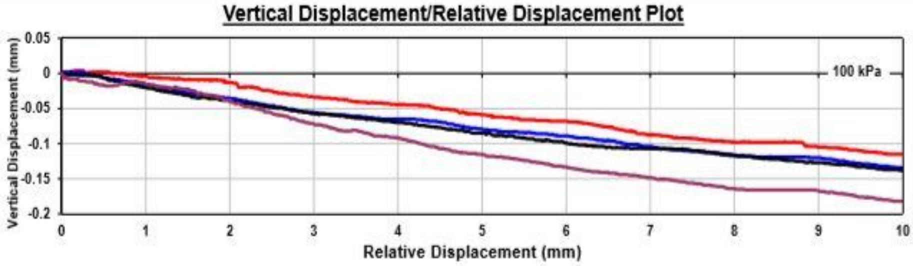
DIRECT SHEAR TEST REPORT

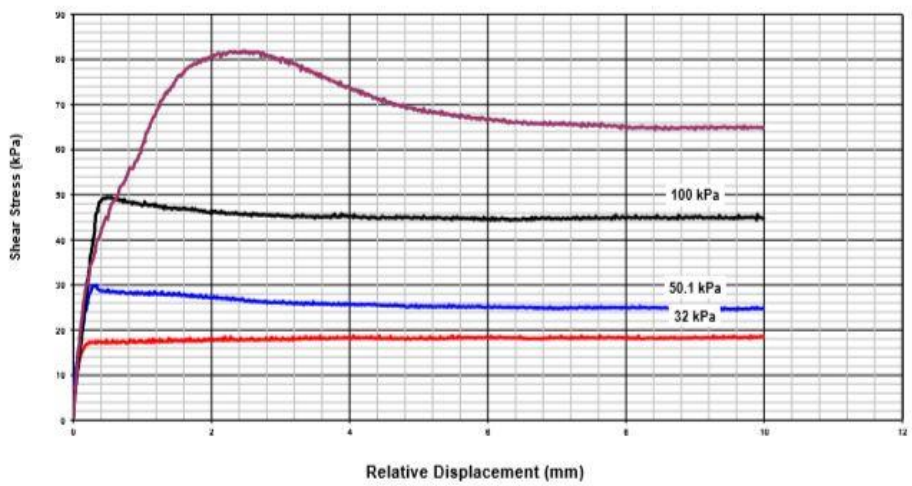
Test Method: AS 1289.6.2.2 / KH2 based on K.H. Head Vol. 2

Client	Dio Antille	**Report No.**	18030849A- DS
		Workorder No	0003998
Address	University of Southern Queensland West St Toowoomba 4350	**Test Date**	5/04/2018
		Report Date	18/04/2018
Project	1006280		
Client ID	Vertisol	**Depth (m)**	Not Supplied
Description	SANDY CLAY - brown	**Sample Type**	Four Individual Soil Specimens - Remoulded as requested by the client.

Vertical Displacement/Relative Displacement Plot



Shear Stress/Displacement Plot



Notes/Remarks: The sample was tested against a supplied steel plate as requested by the client.
Note: Area correction based on square sample equation.

Graph not to scale

Sample/s supplied by the client

Page 1 of 4 REP07301

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C. Channon

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Laboratory No. 9926

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Trilab Pty Ltd ABN 25 065 630 506

ACCURATE QUALITY RESULTS FOR TOMORROW'S ENGINEERING

Trilab — Soil Rock Calibration

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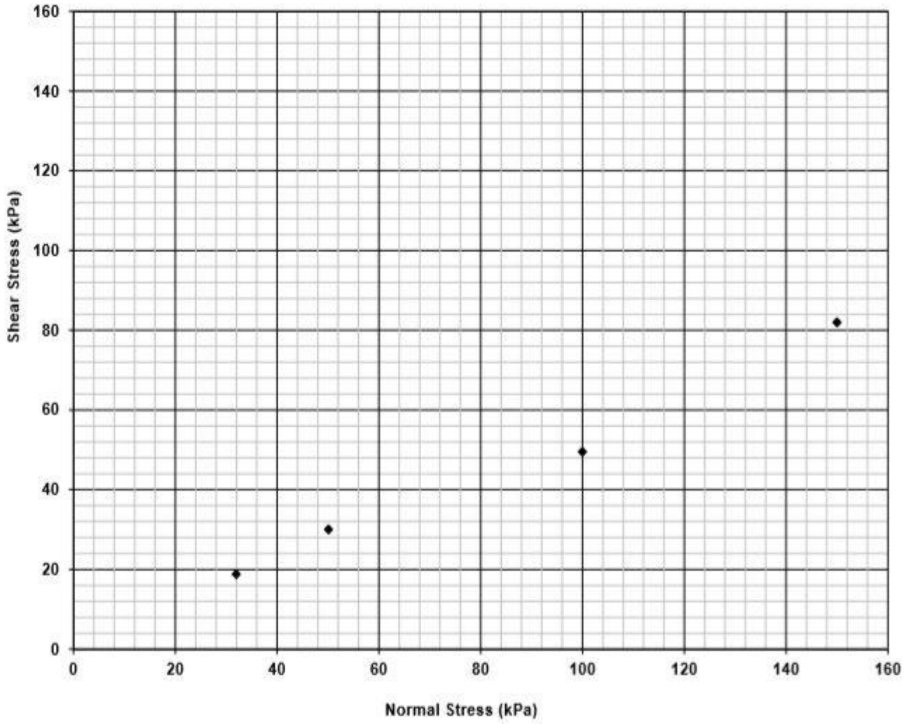
DIRECT SHEAR TEST REPORT

Test Method: AS 1289.6.2.2 / KH2 based on K.H. Head Vol. 2

Client	Dio Antille	**Report No.**	18030849A- DS
Failure Criteria		**Peak**	

Peak - Normal Stress vs Shear Stress



Shear Angle (°)	**27.4**	**Adhesion (kPa)**	**2.0**	**R^2**	**0.994**
Specimen Condition	As Received	Normal Stress (kPa)		Corrected Shear Stress (kPa)	
Specimen Dimensions (mm)	100*100	Stage 1	32.0	18.8	
Rate of Strain (mm/min)	0.008	Stage 2	50.1	30.0	
Initial Moisture Content (%)	39.9	Stage 3	100.0	49.5	
Initial Wet Density(t/m^3)	1.40	Stage 4	150.0	81.9	

Notes/Remarks: The sample was tested against a supplied steel plate as requested by the client.
Note: Area correction based on square sample equation.

Graph not to scale — Sample/s supplied by the client — Page 3 of 4 REP07301

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Laboratory No. 9926

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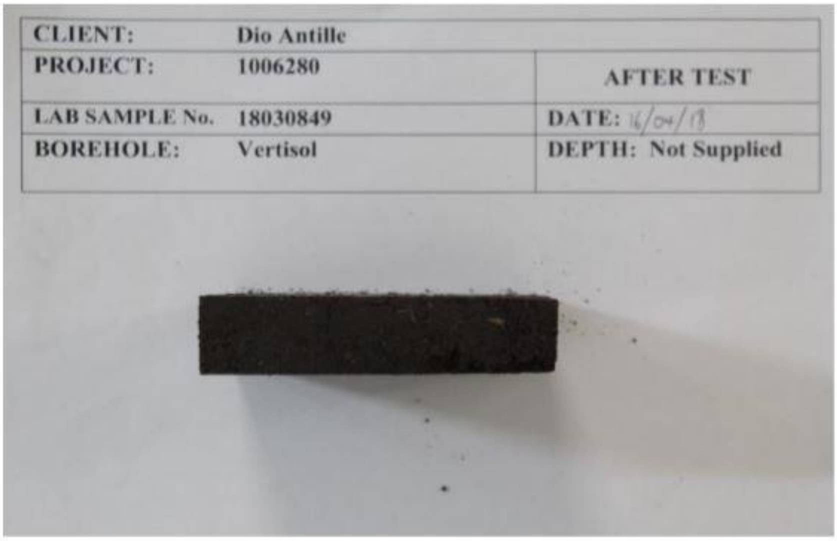
DIRECT SHEAR TEST REPORT

Test Method: AS 1289.6.2.2 / KH2 based on K.H. Head Vol. 2

Client	Dio Antille	**Report No.**	18030849A- DS



Notes/Remarks:

Photo not to scale

Sample/s supplied by the client

Page 4 of 4 REP07301

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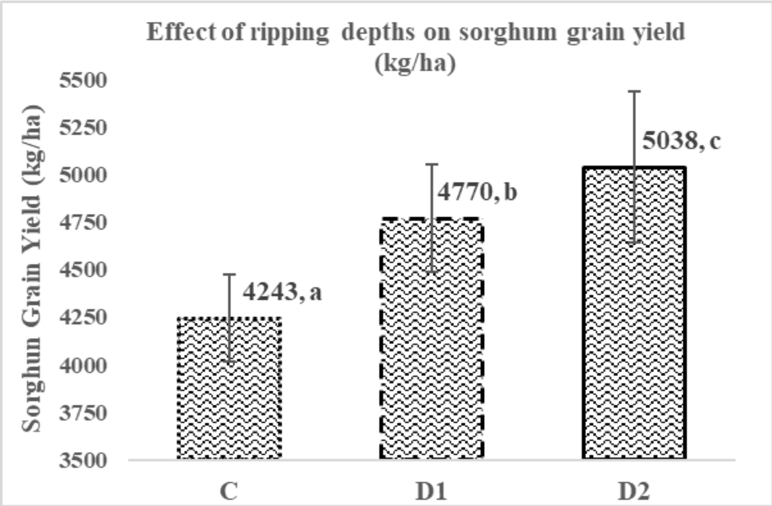
ACCURATE QUALITY RESULTS FOR TOMORROW'S ENGINEERING

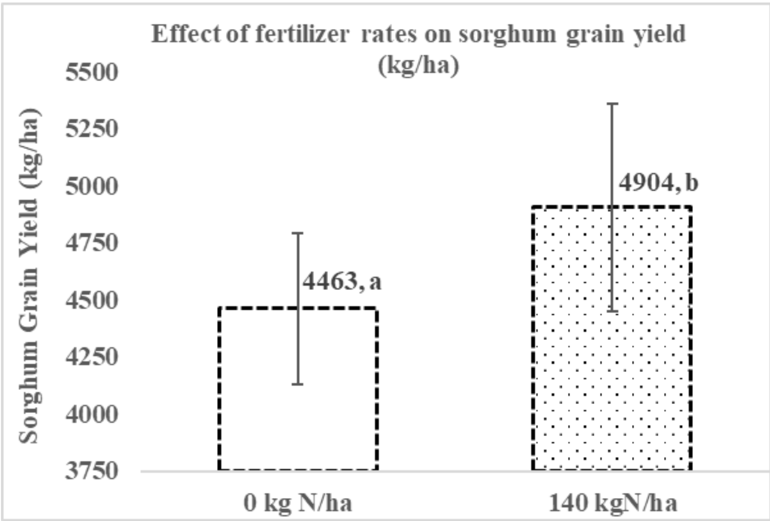
F. Assessing deep ripping - Ag plot site

F.1 Sorghum grain yield

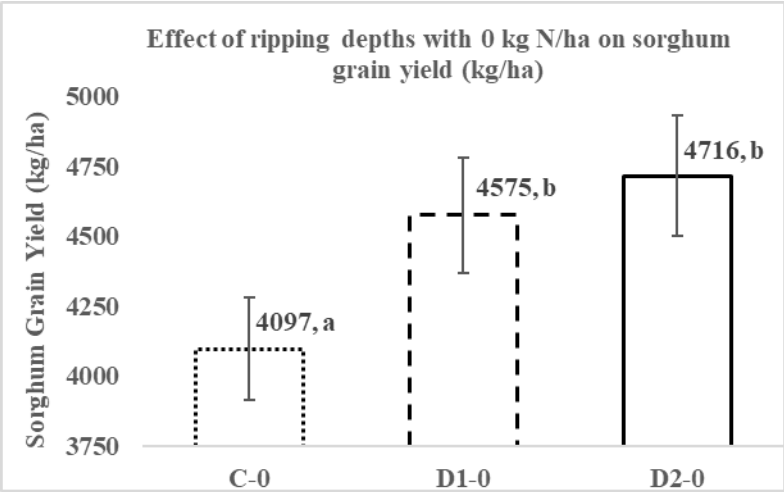
F.1.1 Analysis - Deep ripping effect



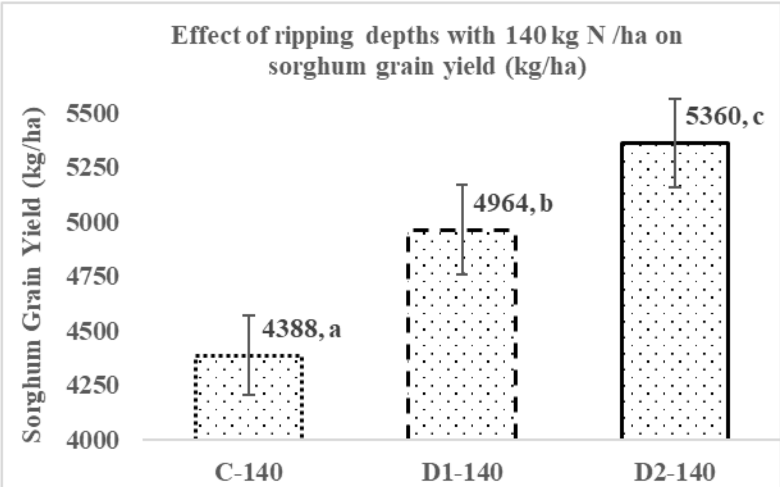
F.1.2 Analysis - Fertiliser rates effect



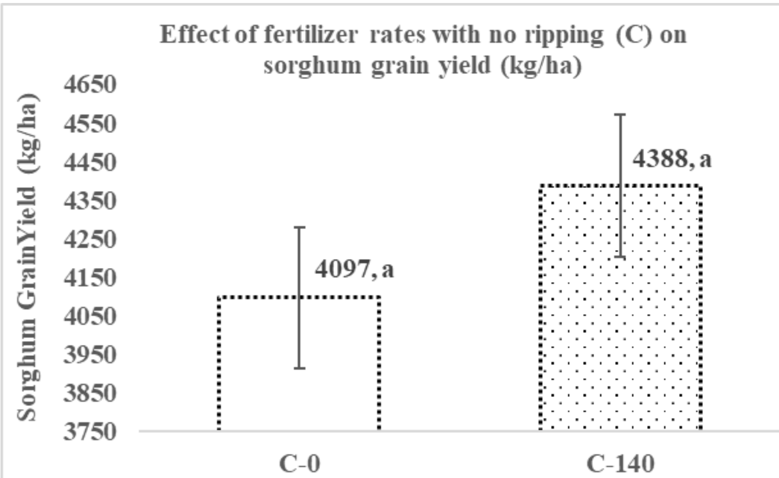
F.1.3 Analysis - Deep ripping with no fertiliser overlapping effect



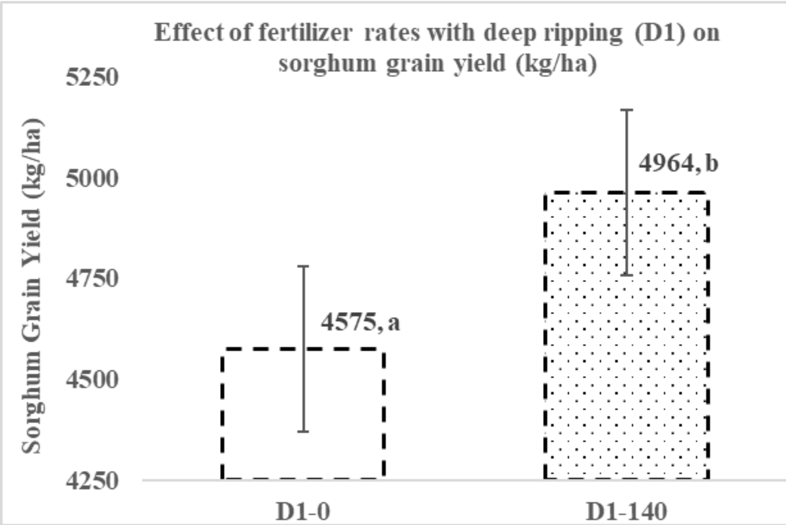
F.1.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



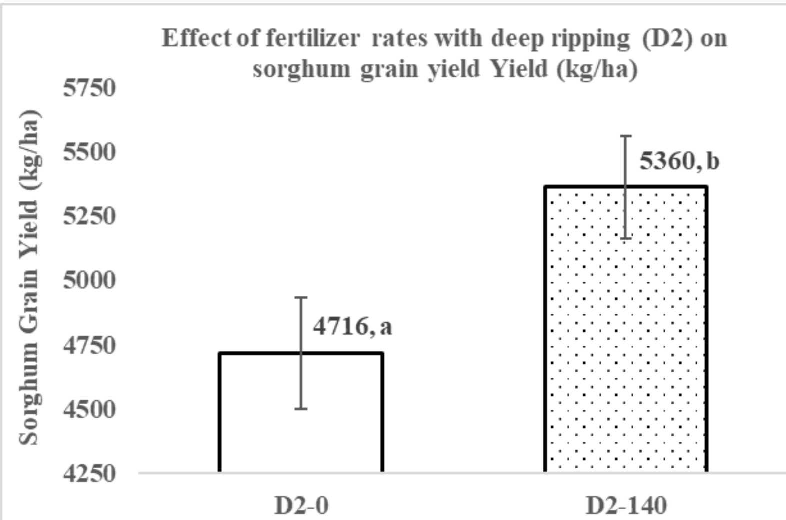
F.1.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.1.6 Analysis - Fertiliser rates with D1 overlapping effect

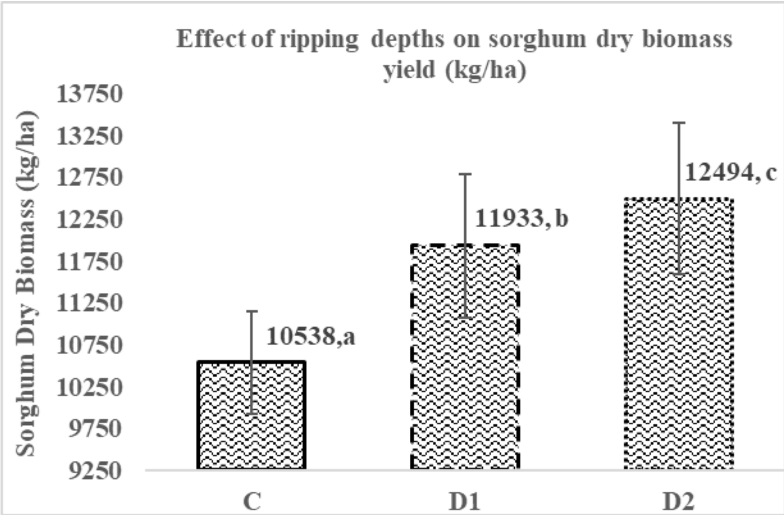


F.1.7 Analysis - Fertiliser rates with D2 overlapping effect

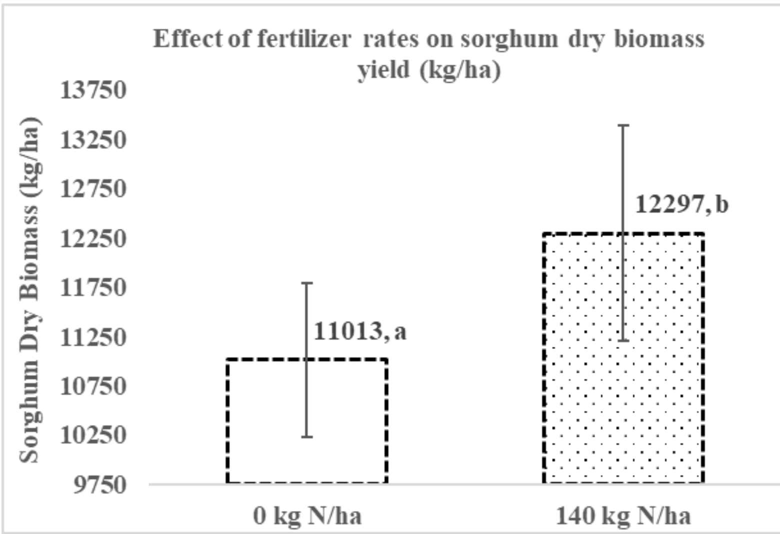


F.2 Sorghum dry biomass yield

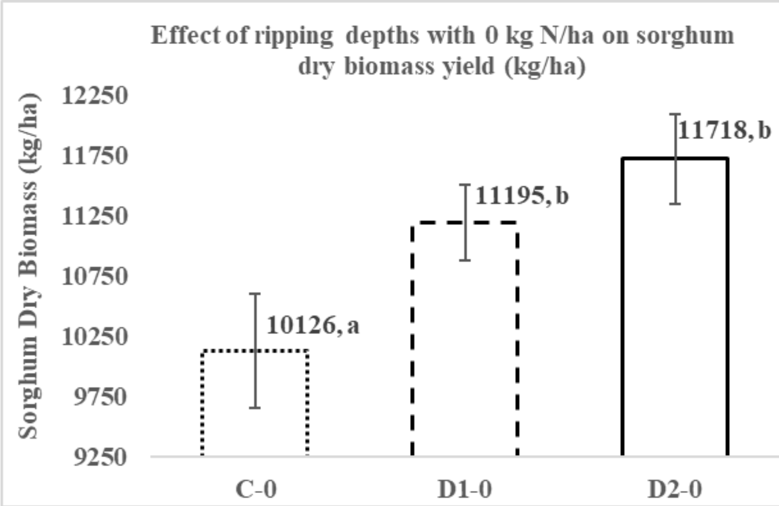
F.2.1 Analysis - Deep ripping effect



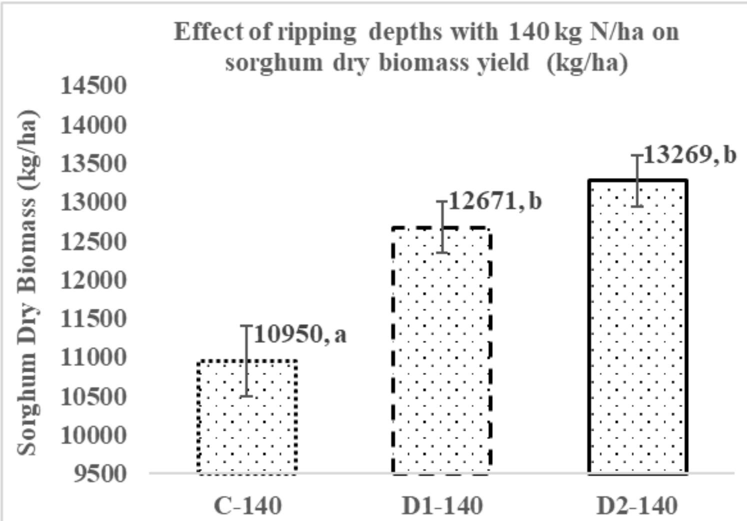
F.2.2 Analysis - Fertiliser rates effect



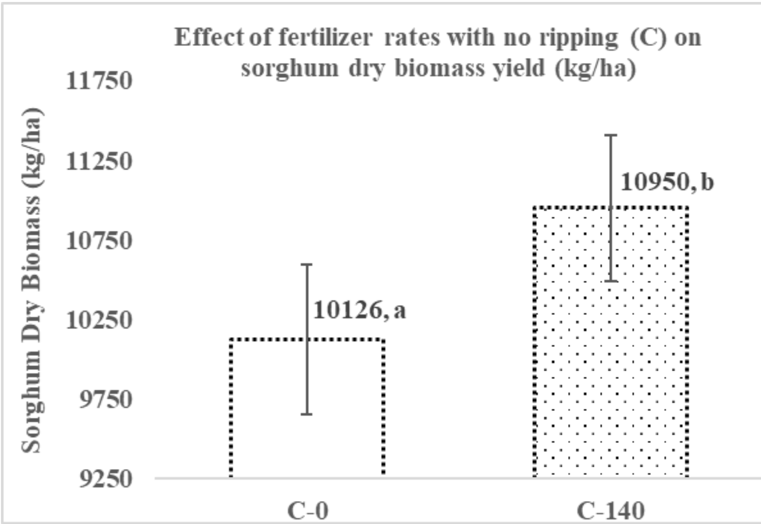
F.2.3 Analysis - Deep ripping with no fertiliser overlapping effect



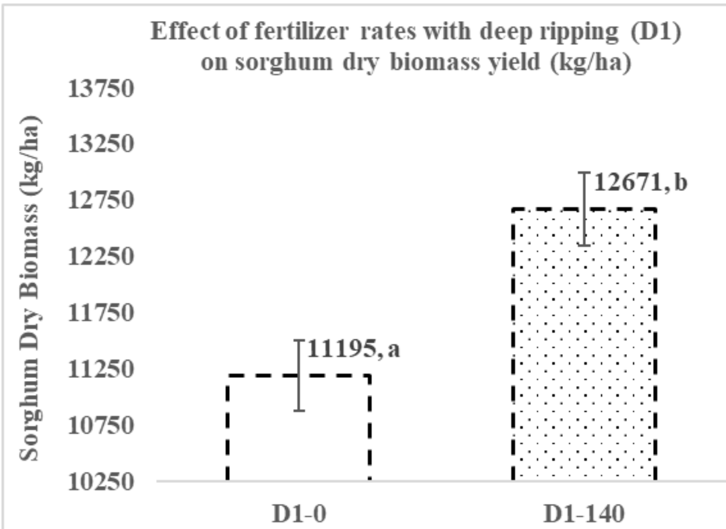
F.2.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



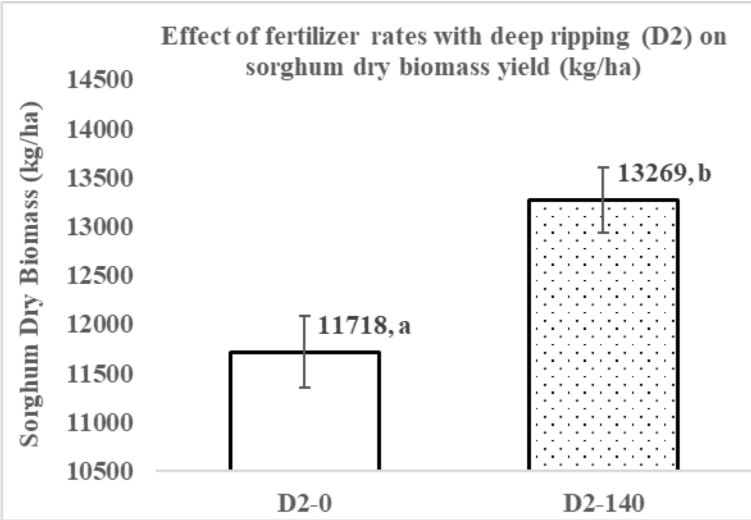
F.2.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.2.6 Analysis - Fertiliser rates with D1 overlapping effect

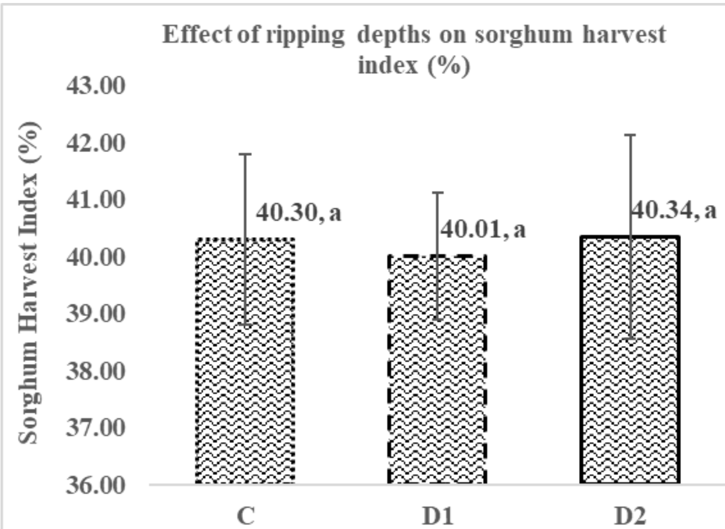


F.2.7 Analysis - Fertiliser rates with D2 overlapping effect

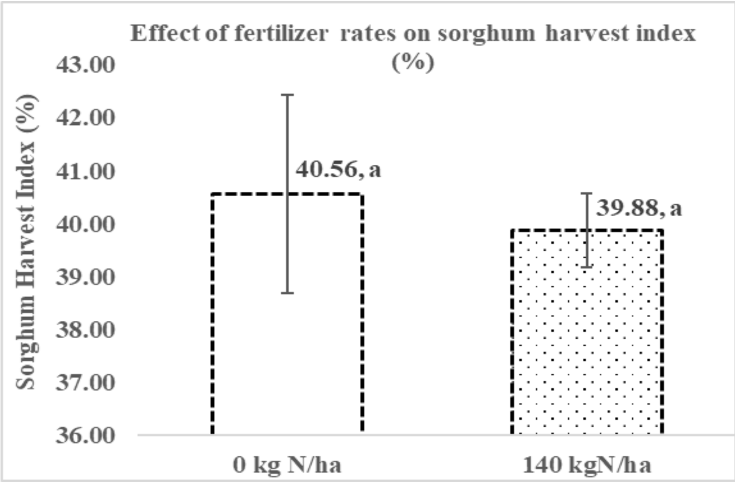


F.3 Sorghum harvest index

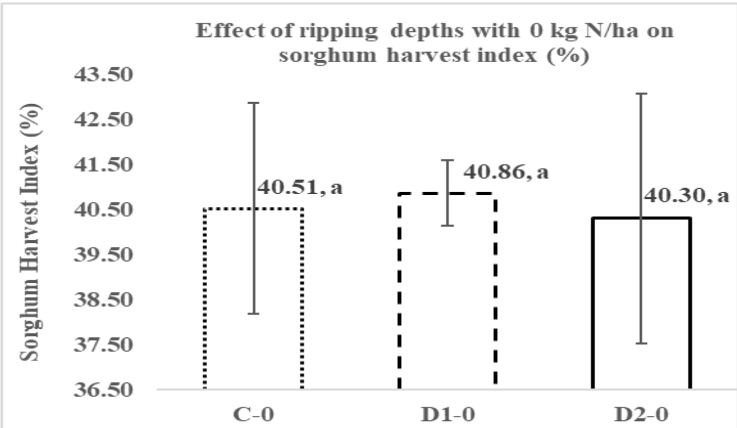
F.3.1 Analysis - Deep ripping effect



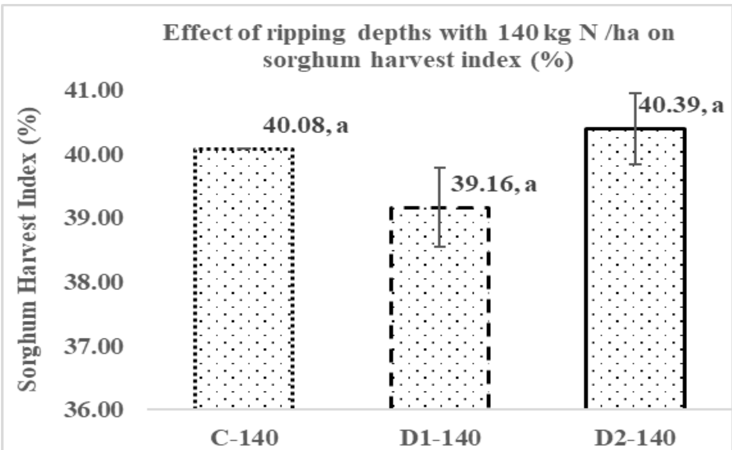
F.3.2 Analysis - Fertiliser rates effect



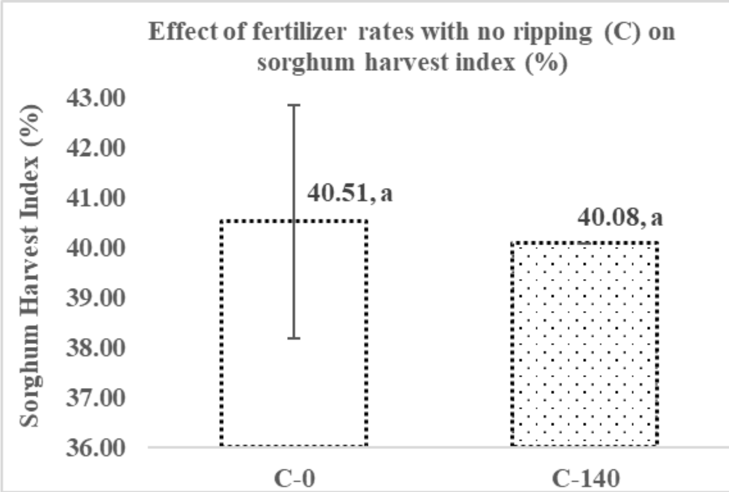
F.3.3 Analysis - Deep ripping with no fertiliser overlapping effect



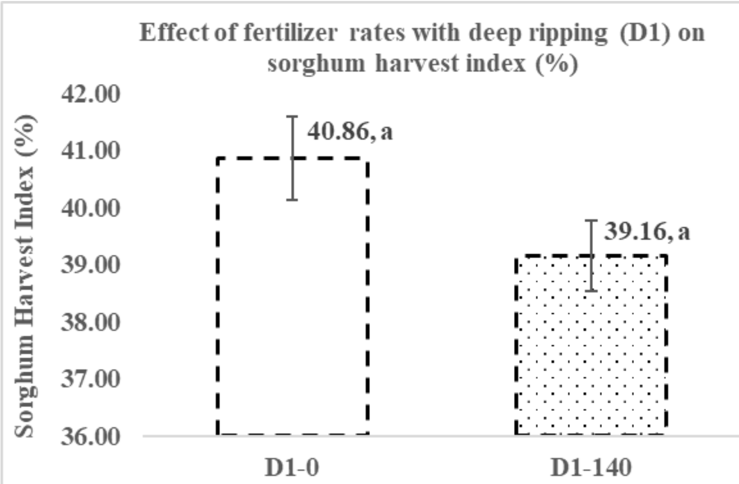
F.3.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



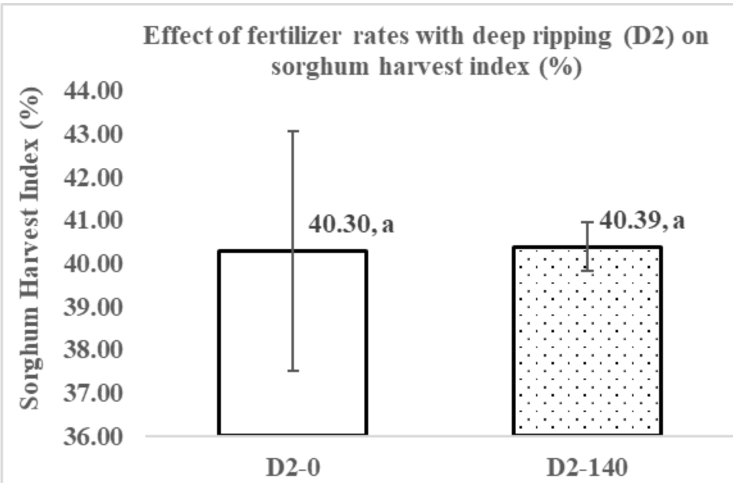
F.3.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.3.6 Analysis - Fertiliser rates with D1 overlapping effect

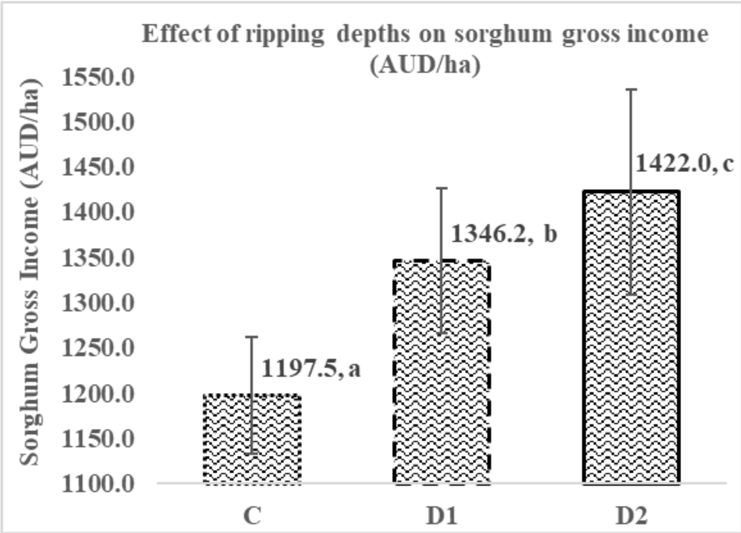


F.3.7 Analysis - Fertiliser rates with D2 overlapping effect

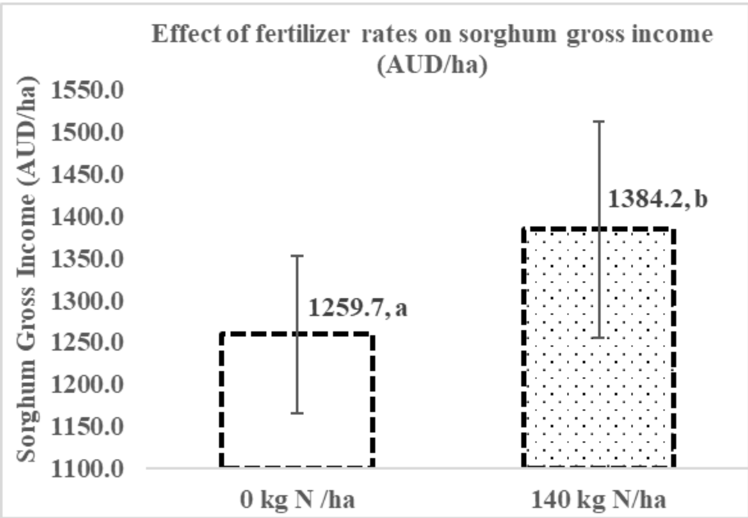


F.4 Sorghum gross income (gross benefit)

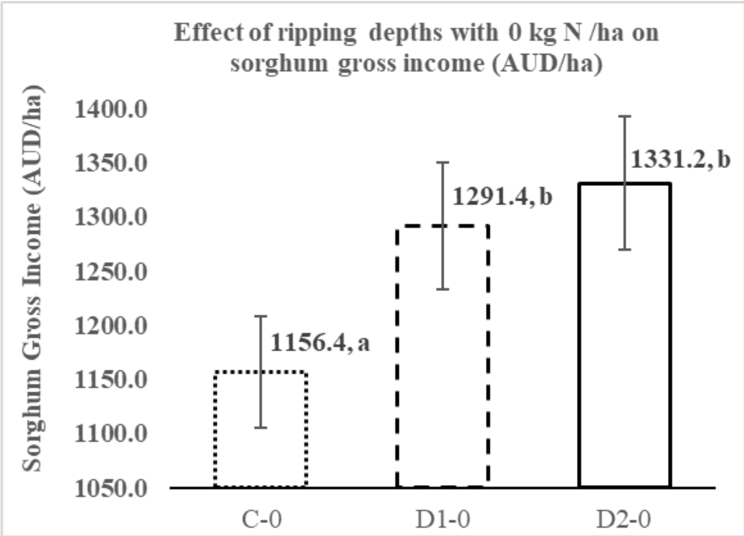
F.4.1 Analysis - Deep ripping effect



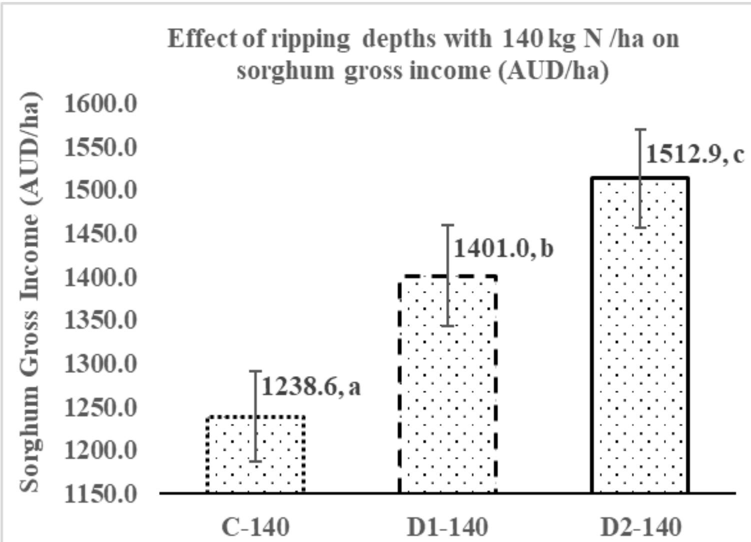
F.4.2 Analysis - Fertiliser rates effect



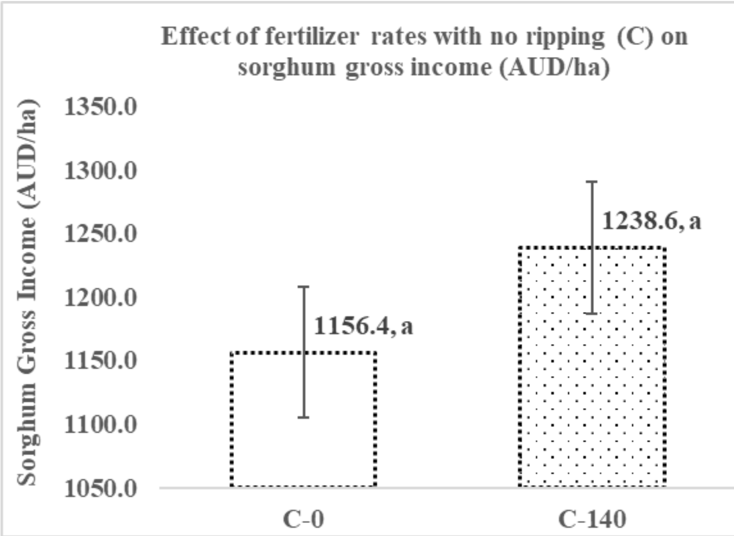
F.4.3 Analysis - Deep ripping with no fertiliser overlapping effect



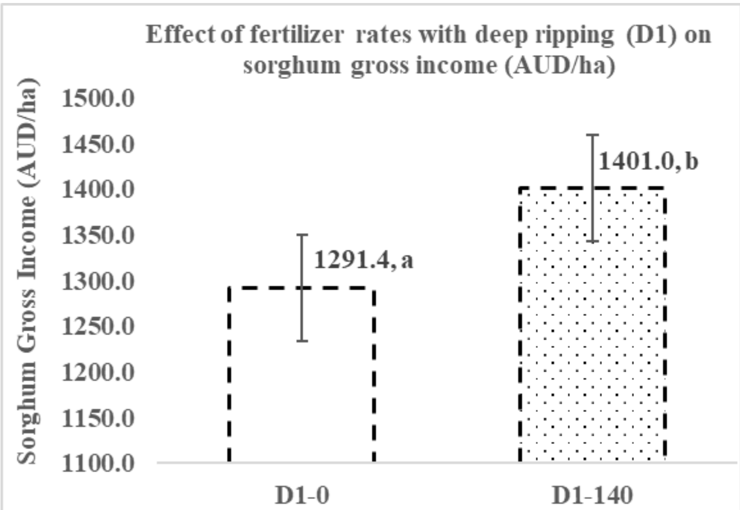
F.4.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



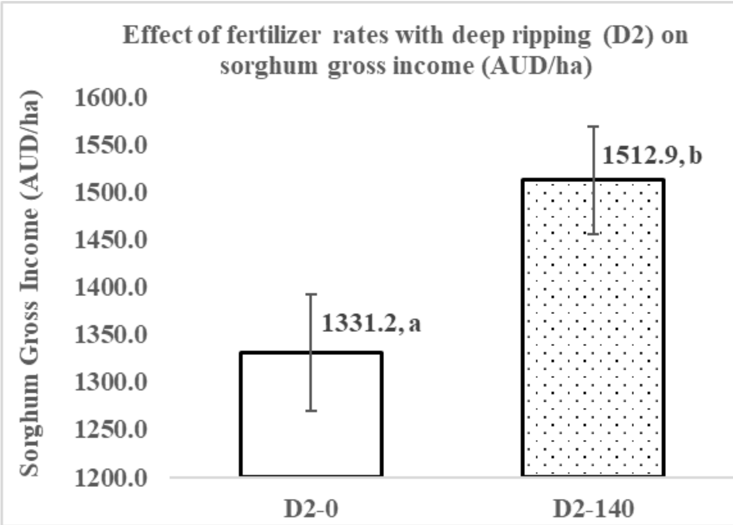
F.4.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.4.6 Analysis - Fertiliser rates with D1 overlapping effect

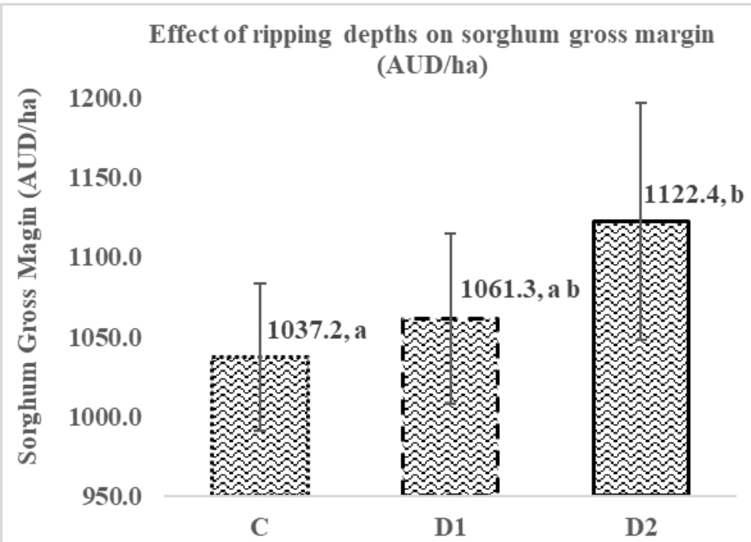


F.4.7 Analysis - Fertiliser rates with D2 overlapping effect

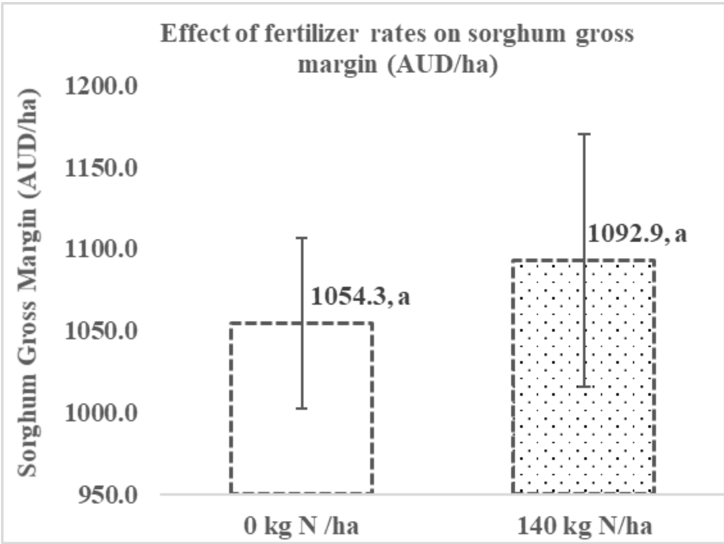


F.5 Sorghum gross margin (net benefit)

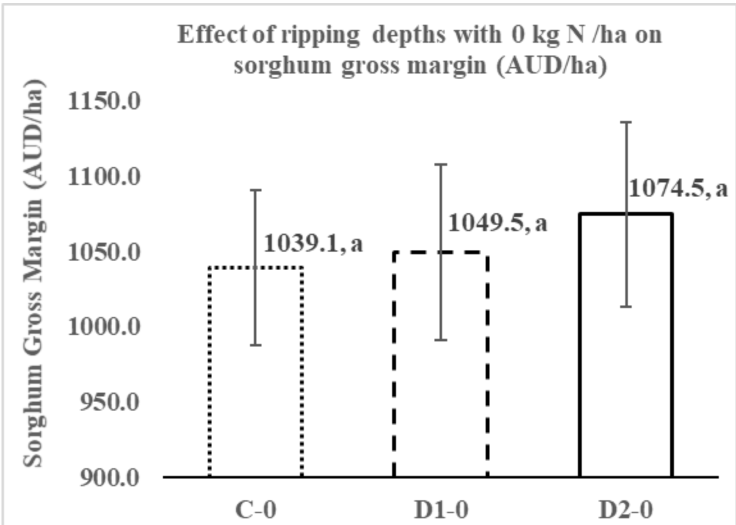
F.5.1 Analysis - Deep ripping effect



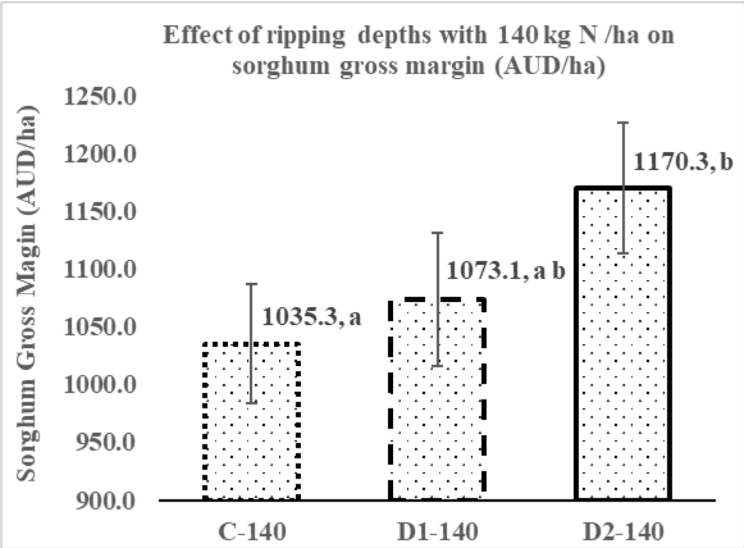
F.5.2 Analysis - Fertiliser rates effect



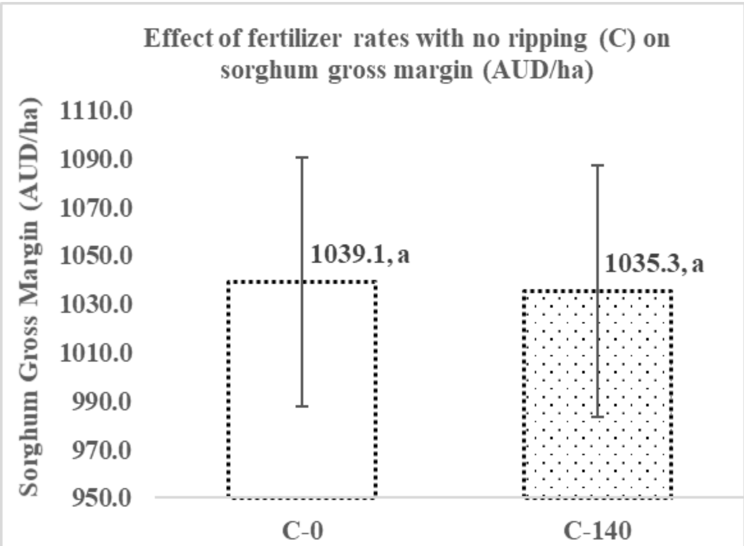
F.5.3 Analysis - Deep ripping with no fertiliser overlapping effect



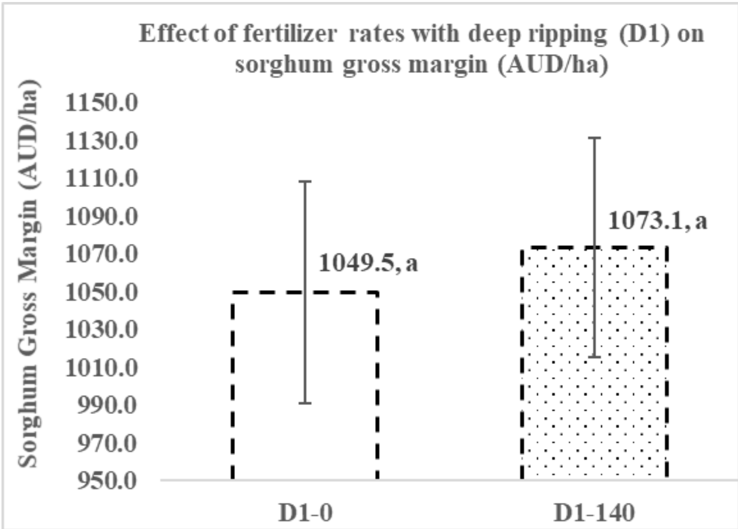
F.5.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



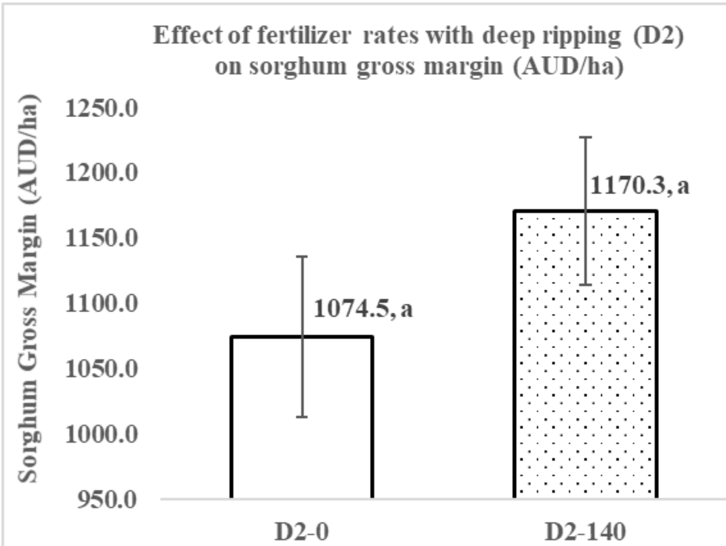
F.5.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.5.6 Analysis - Fertiliser rates with D1 overlapping effect

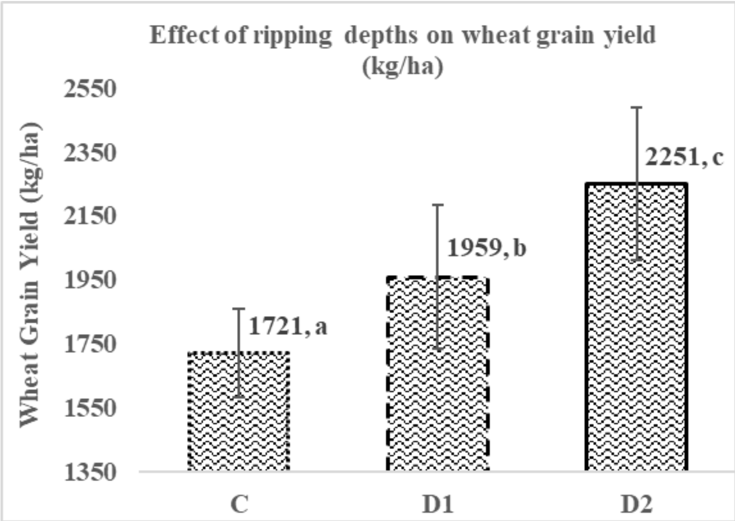


F.5.7 Analysis - Fertiliser rates with D2 overlapping effect

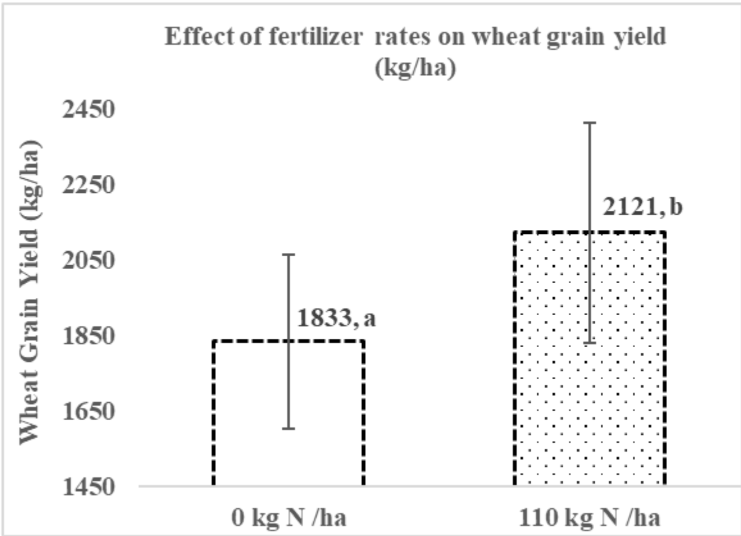


F.6 Wheat grain yield

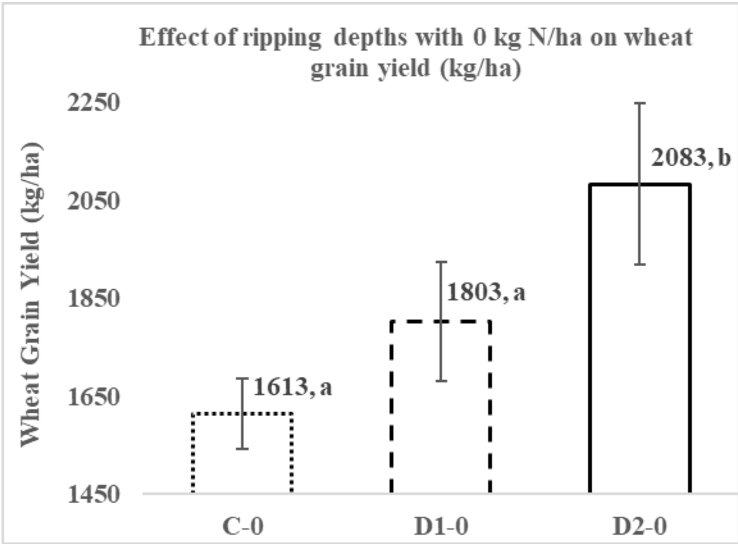
F.6.1 Analysis - Deep ripping effect



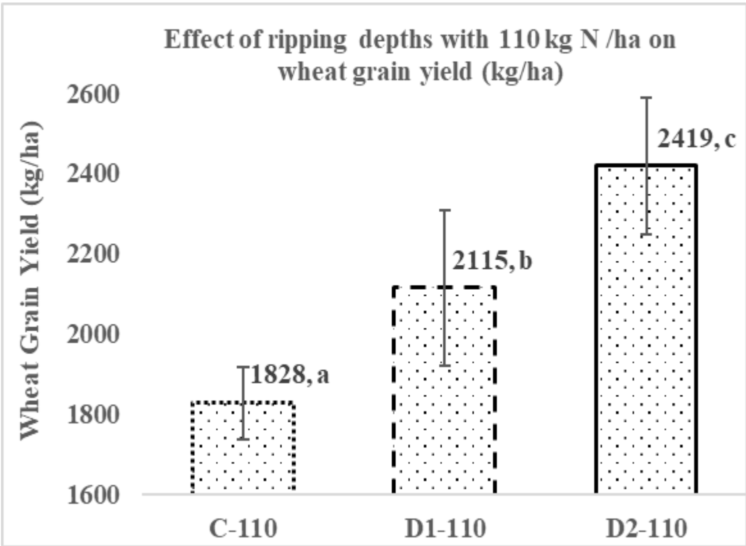
F.6.2 Analysis - Fertiliser rates effect



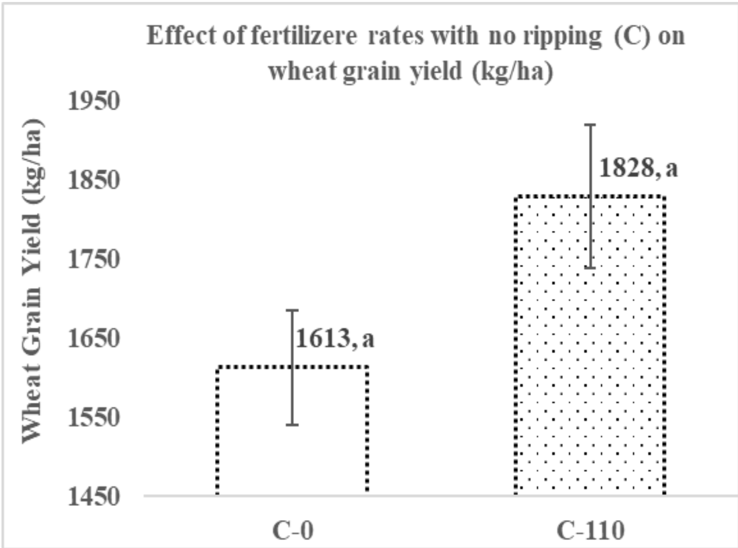
F.6.3 Analysis - Deep ripping with no fertiliser overlapping effect



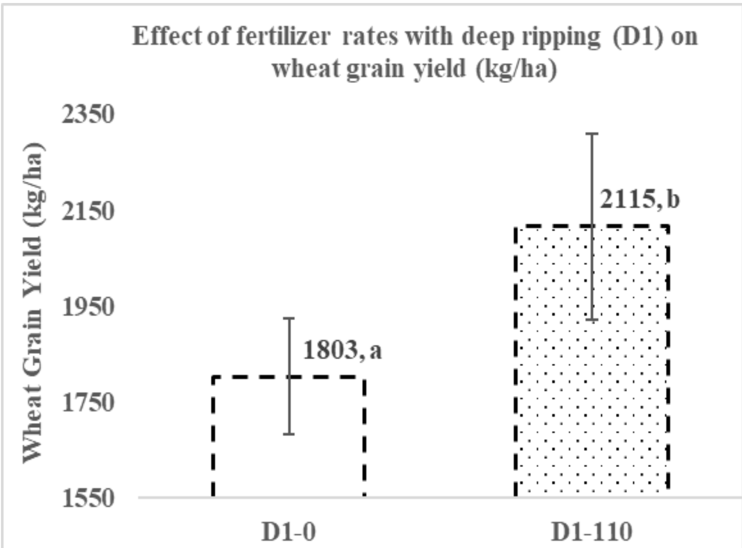
F.6.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



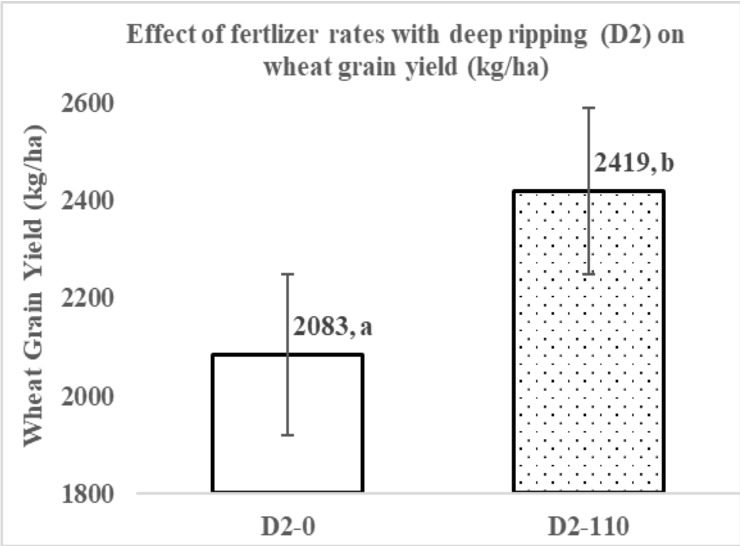
F.6.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.6.6 Analysis - Fertiliser rates with D1 overlapping effect

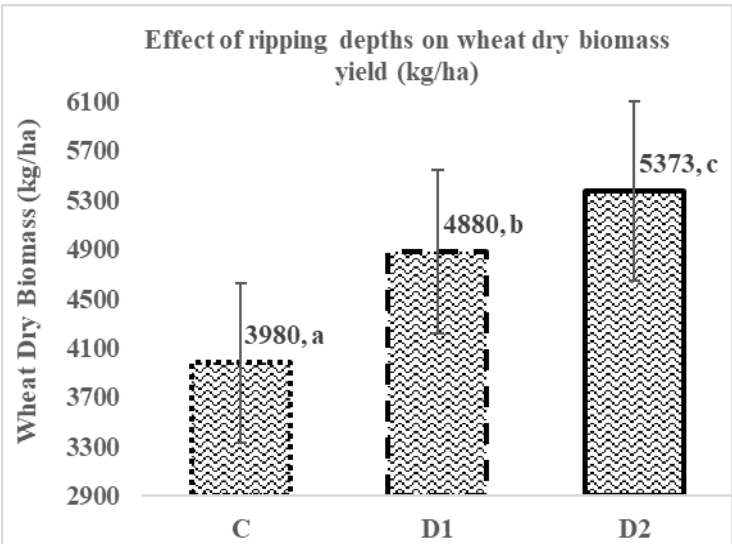


F.6.7 Analysis - Fertiliser rates with D2 overlapping effect

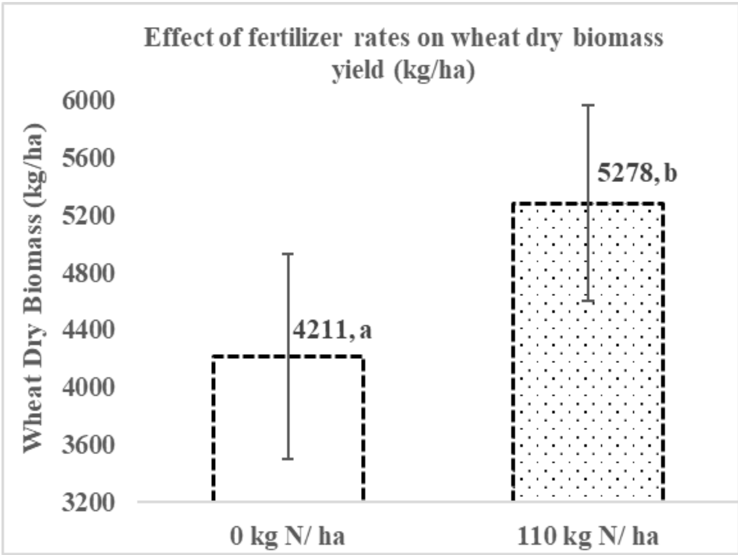


F.7 Wheat dry biomass yield

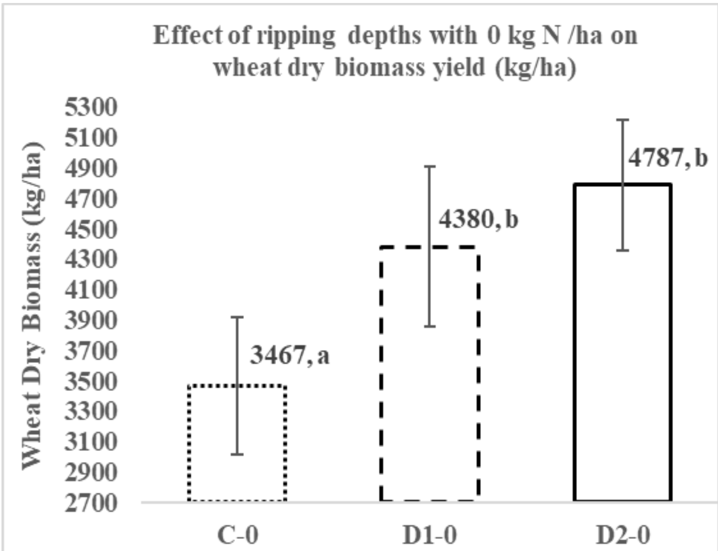
F.7.1 Analysis - Deep ripping effect



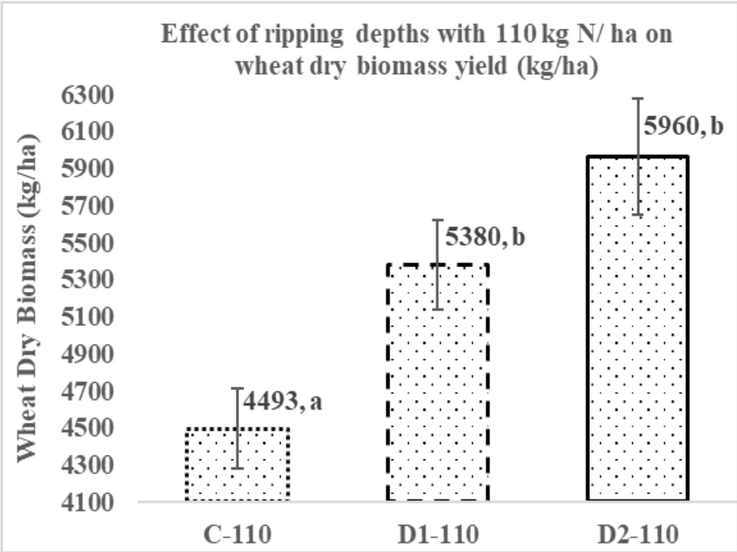
F.7.2 Analysis - Fertiliser rates effect



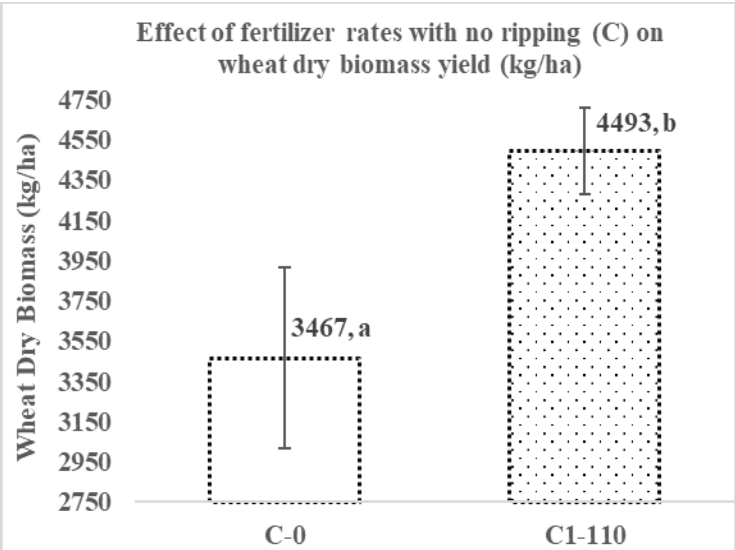
F.7.3 Analysis - Deep ripping with no fertiliser overlapping effect



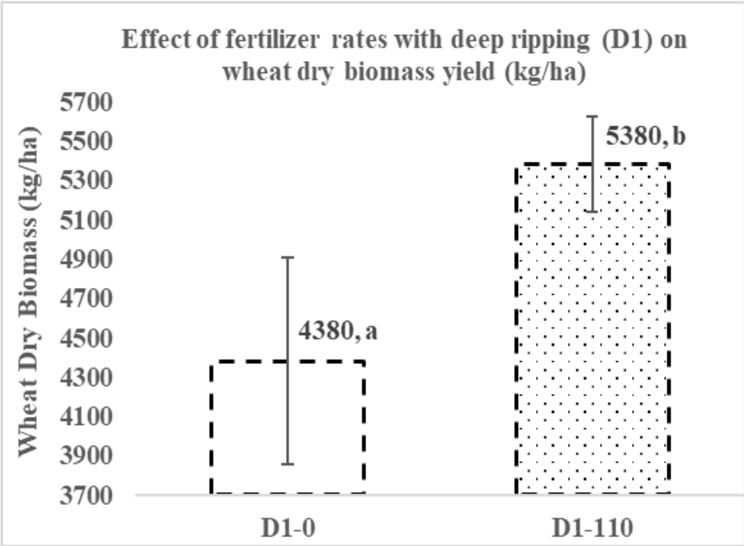
F.7.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



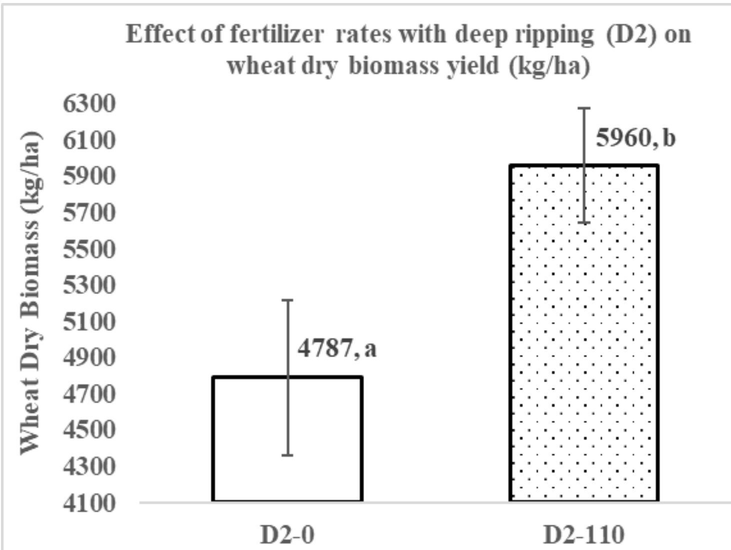
F.7.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.7.6 Analysis - Fertiliser rates with D1 overlapping effect

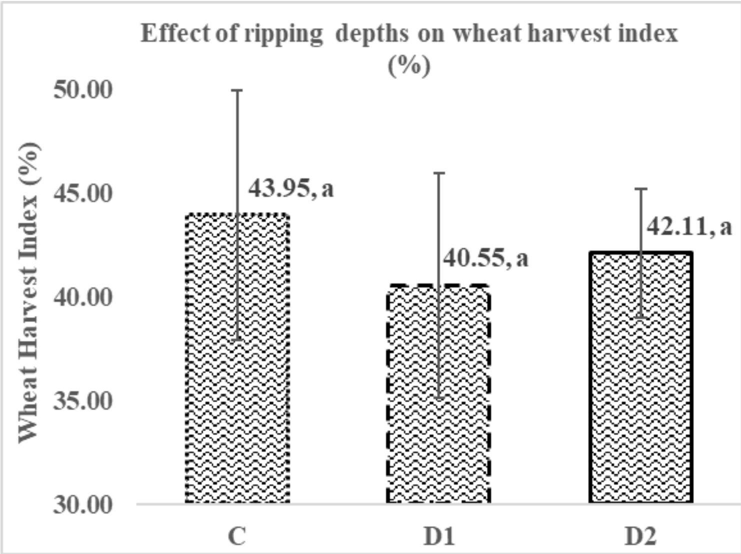


F.7.7 Analysis - Fertiliser rates with D2 overlapping effect

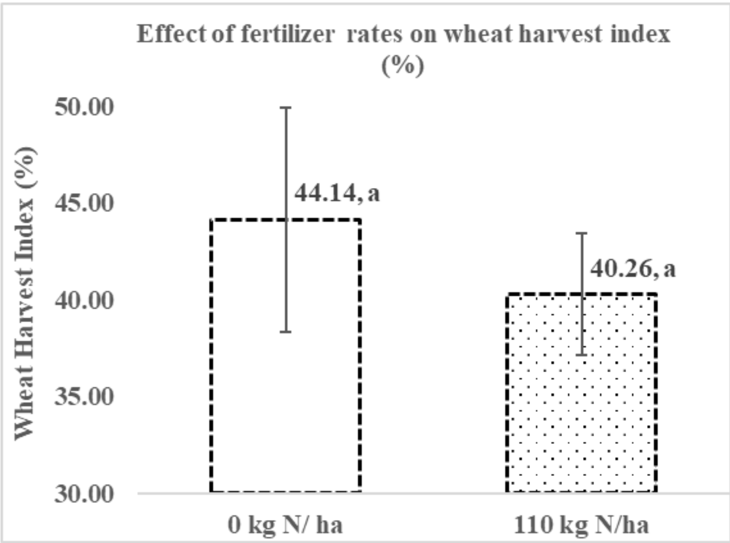


F.8 Wheat harvest index

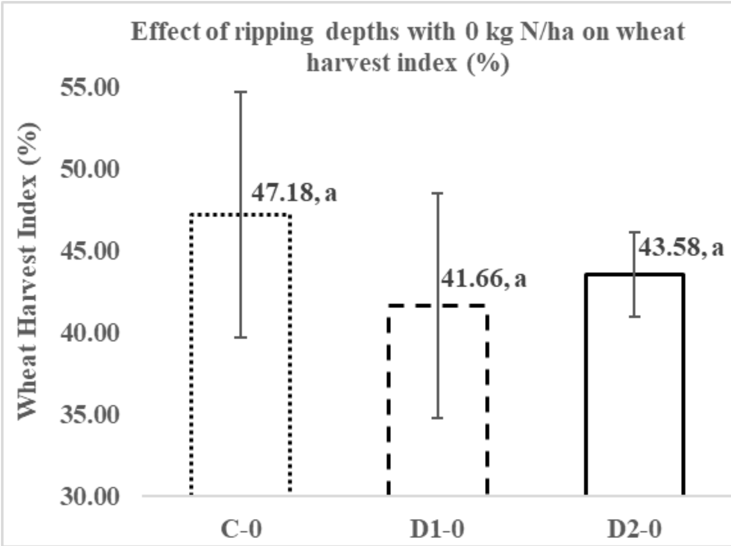
F.8.1 Analysis - Deep ripping effect



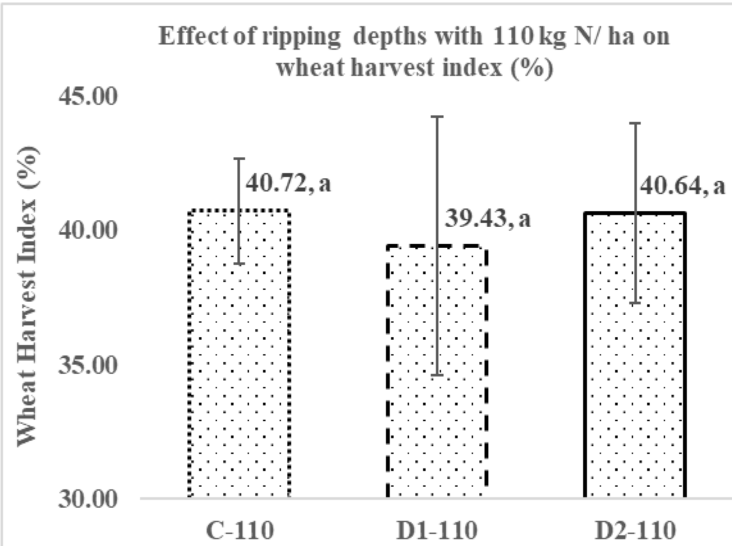
F.8.2 Analysis - Fertiliser rates effect



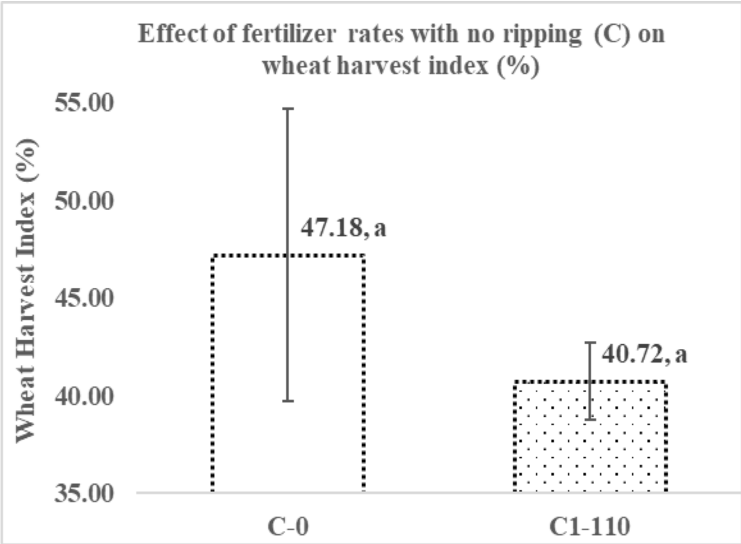
F.8.3 Analysis - Deep ripping with no fertiliser overlapping effect



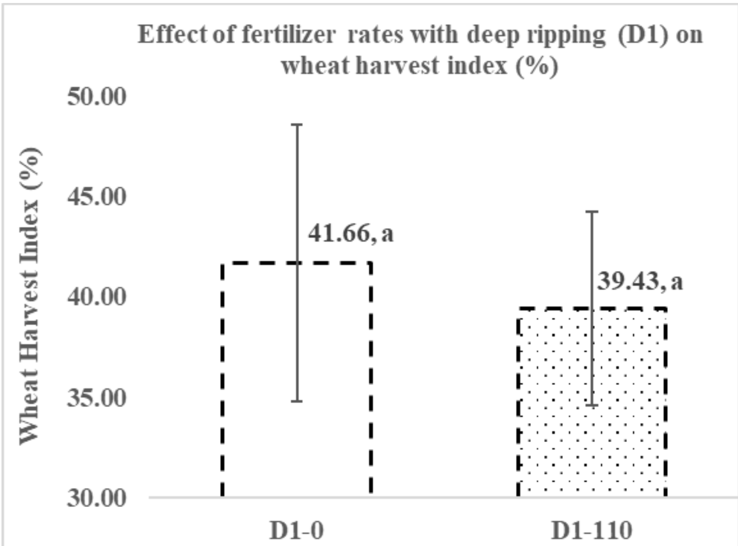
F.8.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



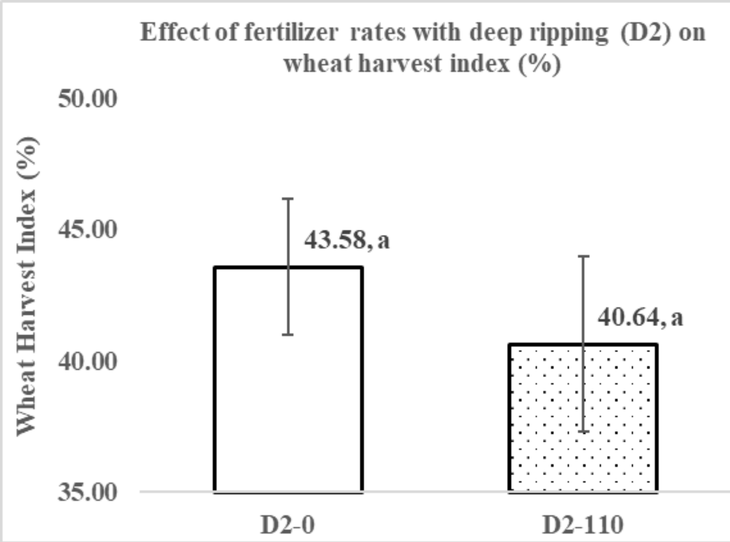
F.8.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.8.6 Analysis - Fertiliser rates with D1 overlapping effect

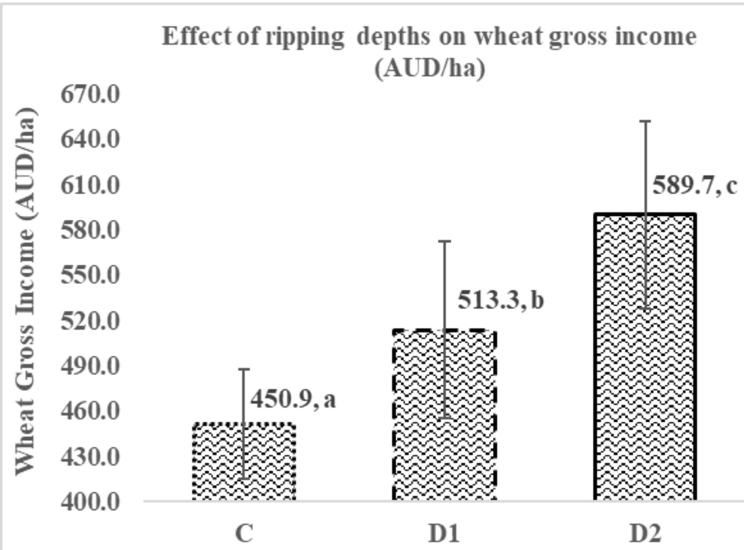


F.8.7 Analysis - Fertiliser rates with D2 overlapping effect

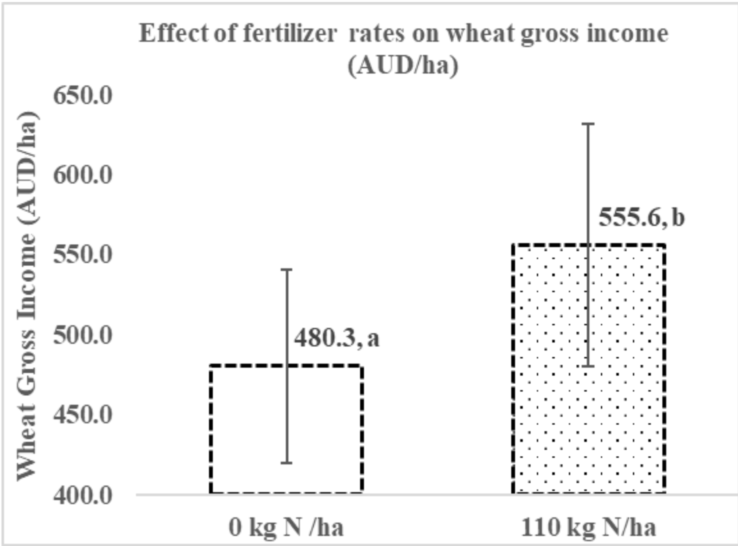


F.9 Wheat gross income (gross benefit)

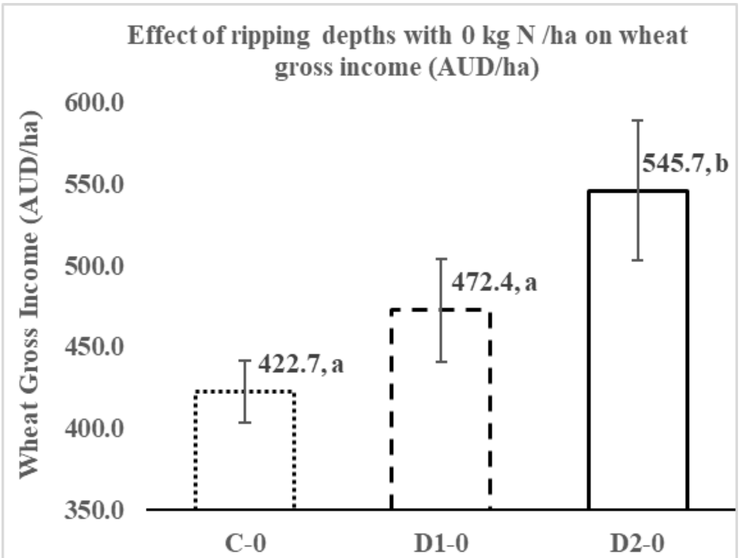
F.9.1 Analysis - Deep ripping effect



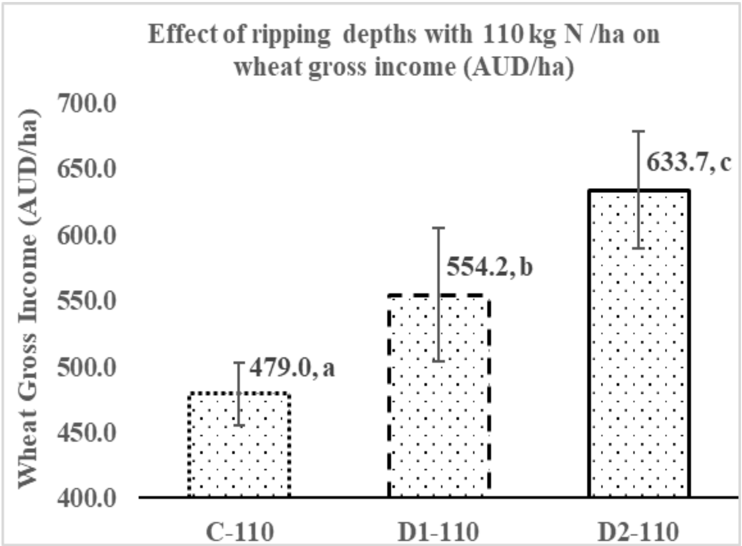
F.9.2 Analysis - Fertiliser rates effect



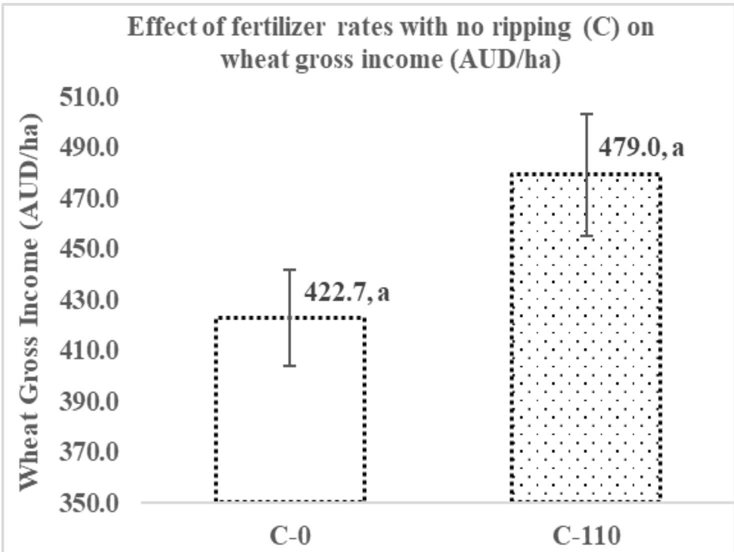
F.9.3 Analysis - Deep ripping with no fertiliser overlapping effect



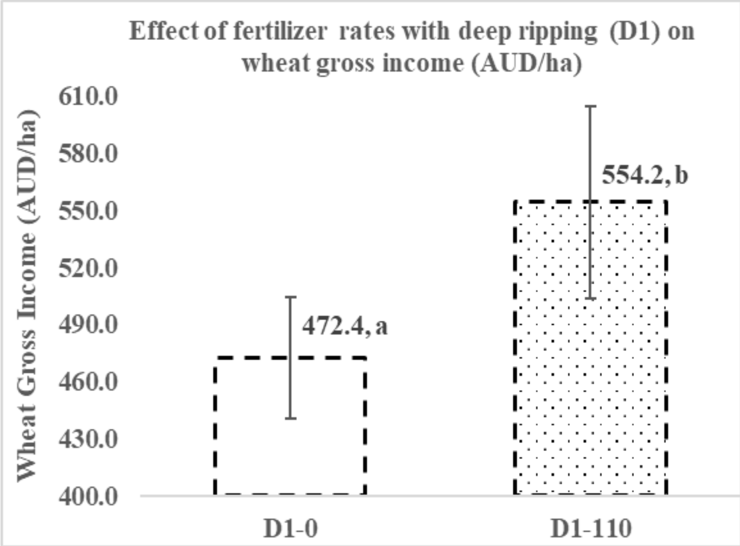
F.9.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



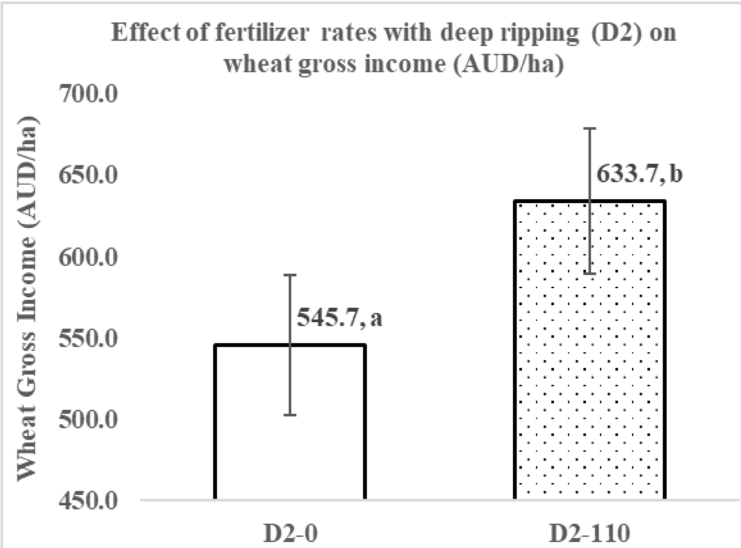
F.9.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.9.6 Analysis - Fertiliser rates with D1 overlapping effect

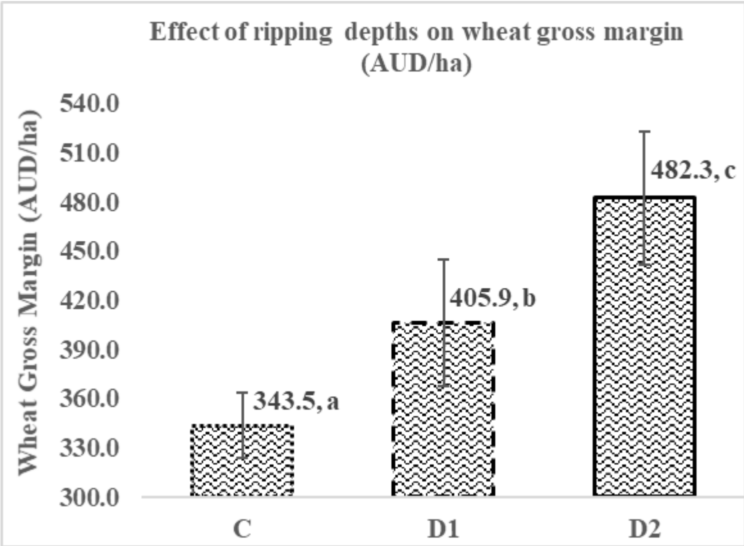


F.9.7 Analysis - Fertiliser rates with D2 overlapping effect

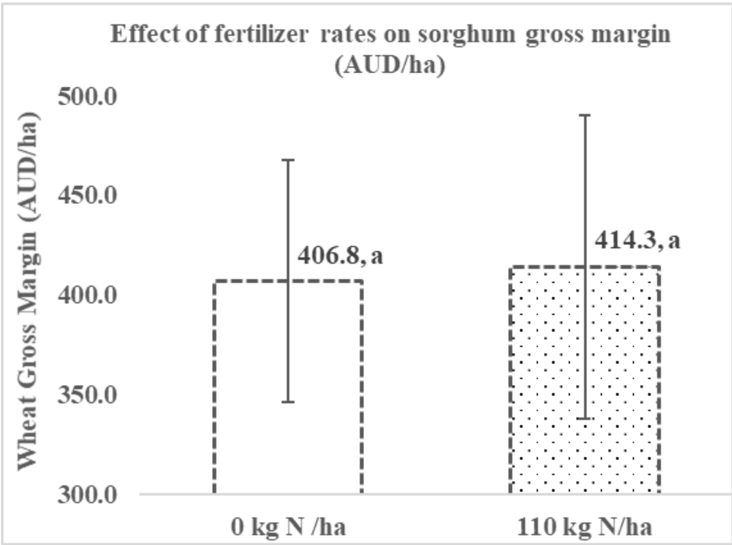


F.10 Wheat gross margin (net benefit)

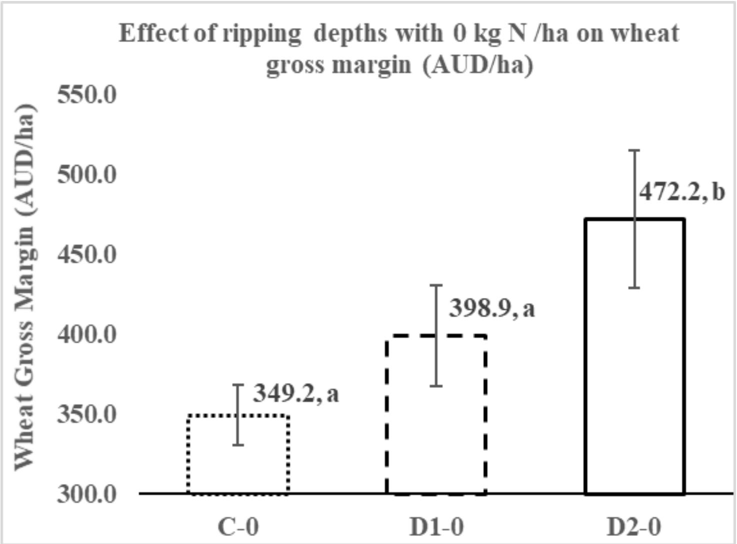
F.10.1 Analysis - Deep ripping effect



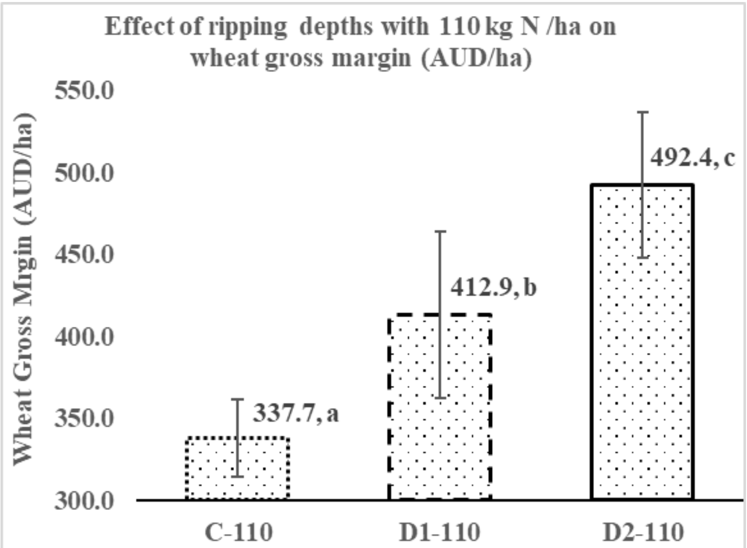
F.10.2 Analysis - Fertiliser rates effect



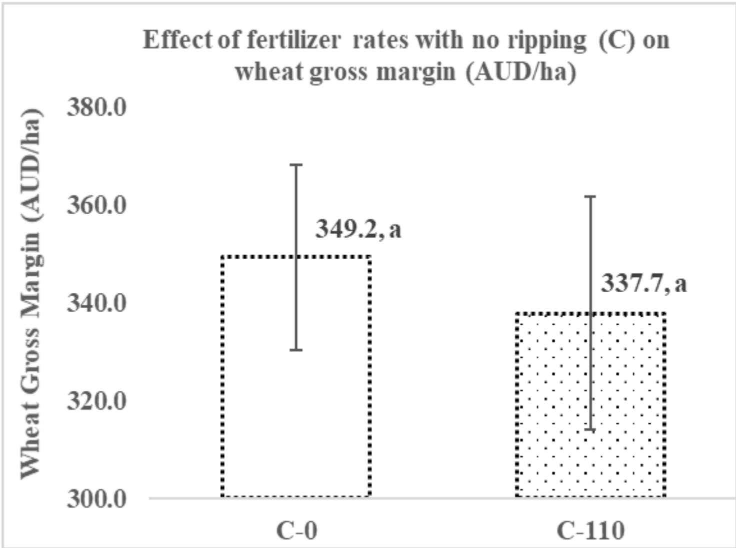
F.10.3 Analysis - Deep ripping with no fertiliser overlapping effect



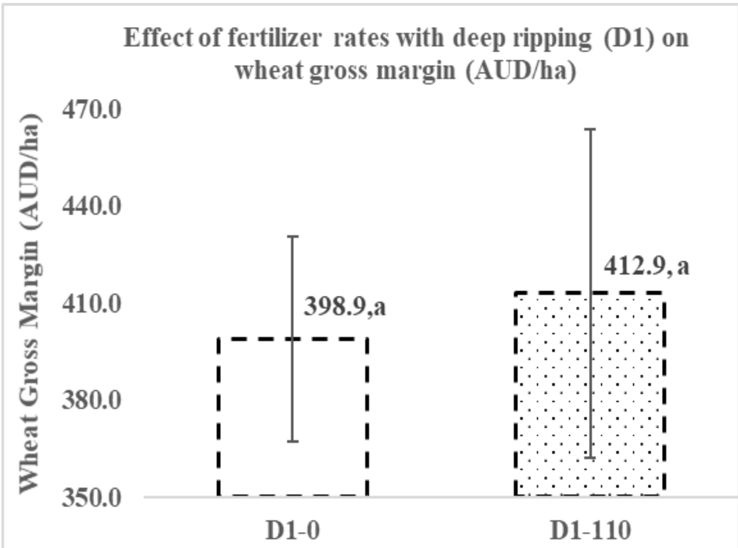
F.10.4 Analysis - Deep ripping with optimum fertiliser rate overlapping effect



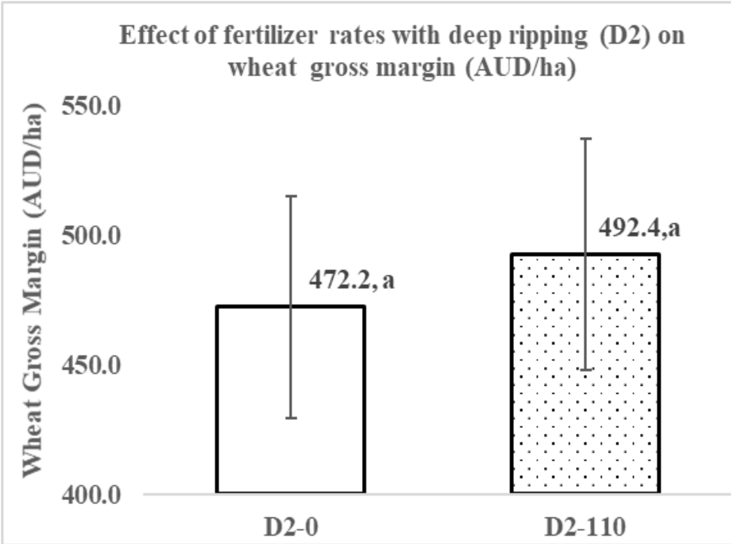
F.10.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.10.6 Analysis - Fertiliser rates with D1 overlapping effect

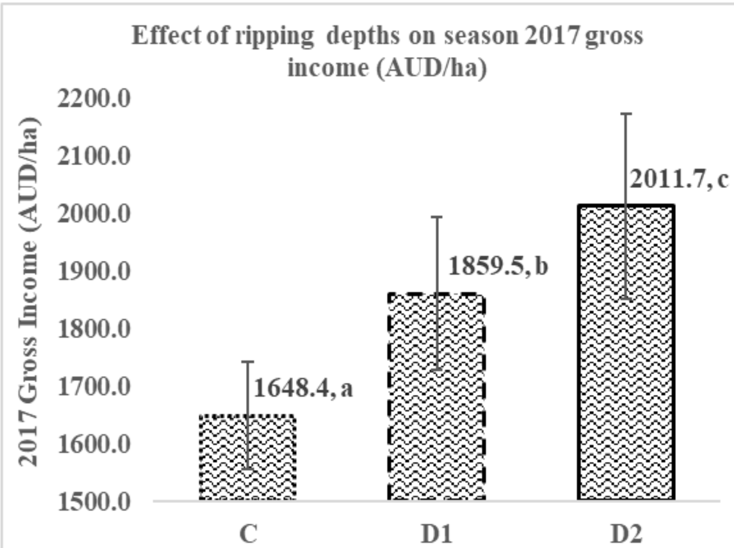


F.10.7 Analysis - Fertiliser rates with D2 overlapping effect

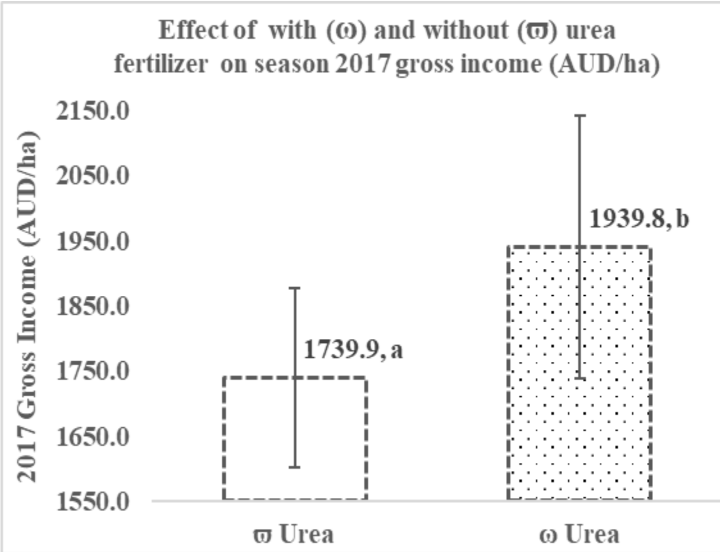


F.11 2017 season gross income (gross benefit)

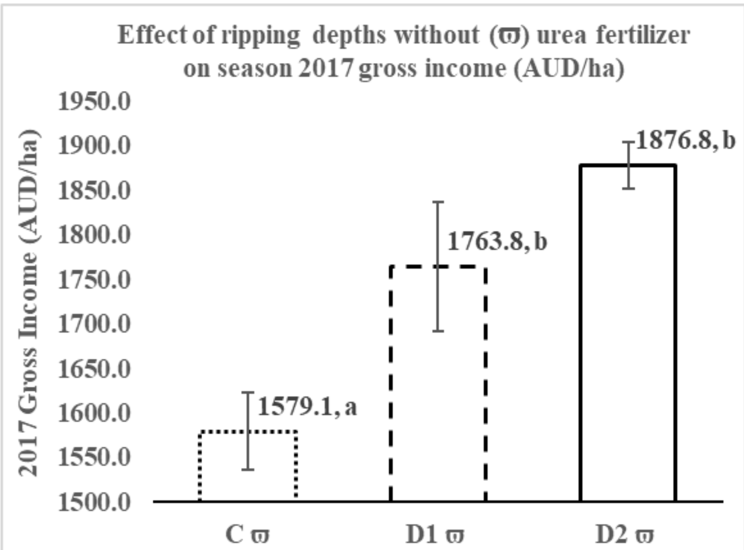
F.11.1 Analysis - Deep ripping effect



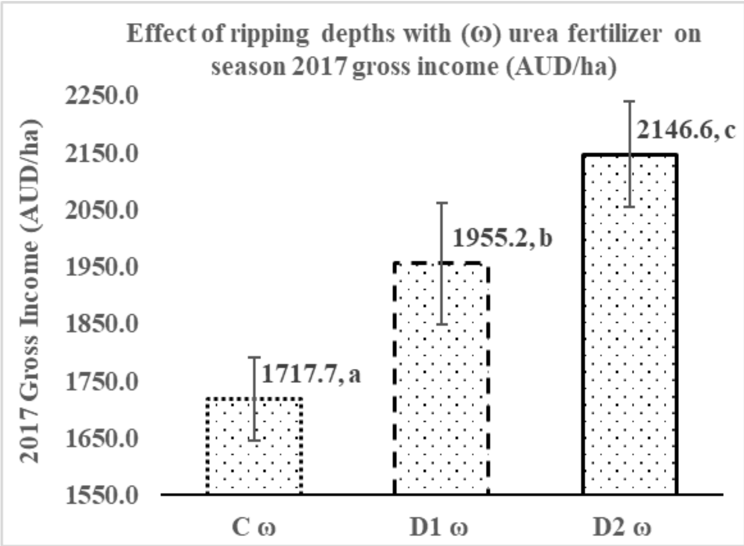
F.11.2 Analysis - Fertiliser rates effect



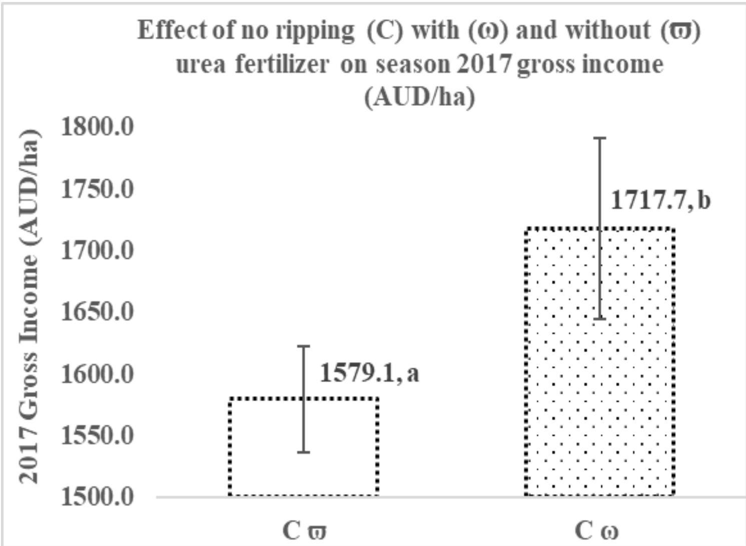
F.11.3 Analysis - Deep ripping with no fertiliser overlapping effect



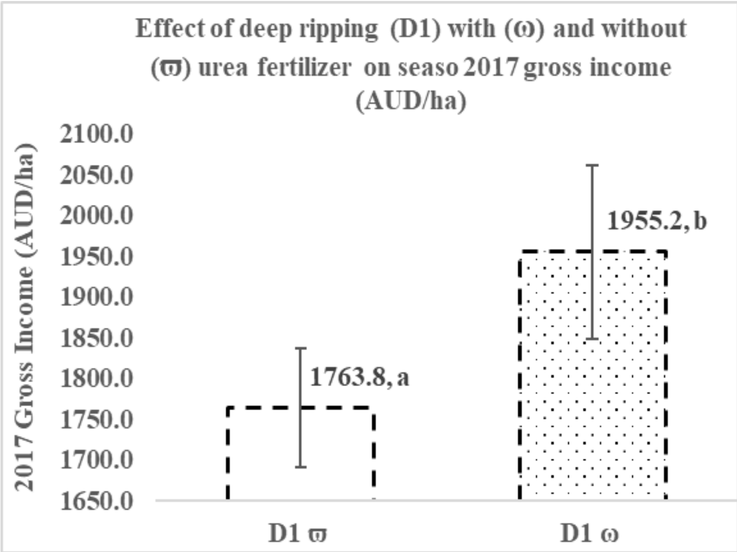
F.11.4 Analysis - Deep ripping with optimum fertiliser rates overlapping effect



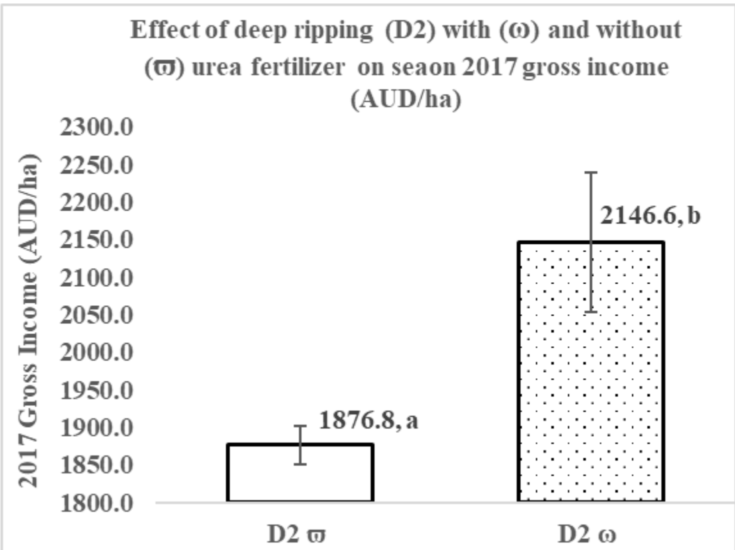
F.11.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.11.6 Analysis - Fertiliser rates with D1 overlapping effect

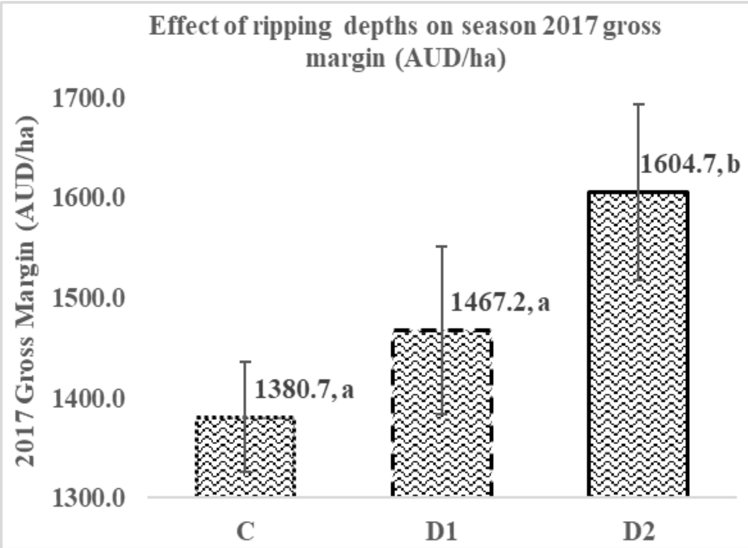


F.11.7 Analysis - Fertiliser rates with D2 overlapping effect

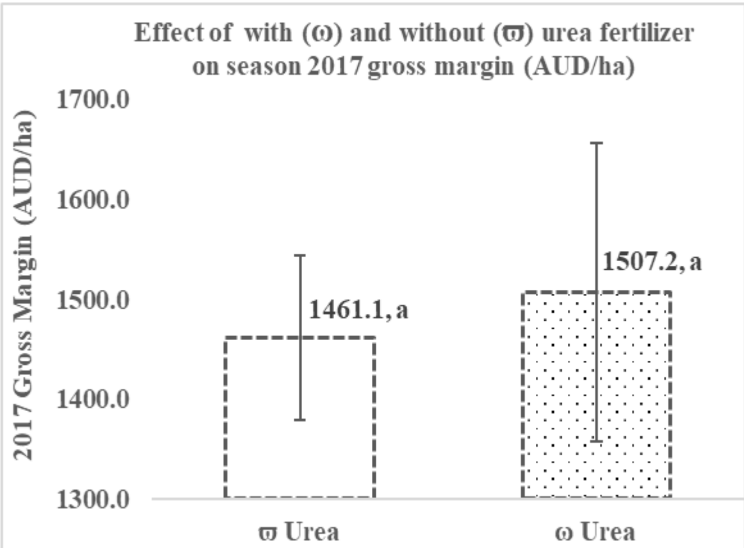


F.12 2017 season gross margin (net benefit)

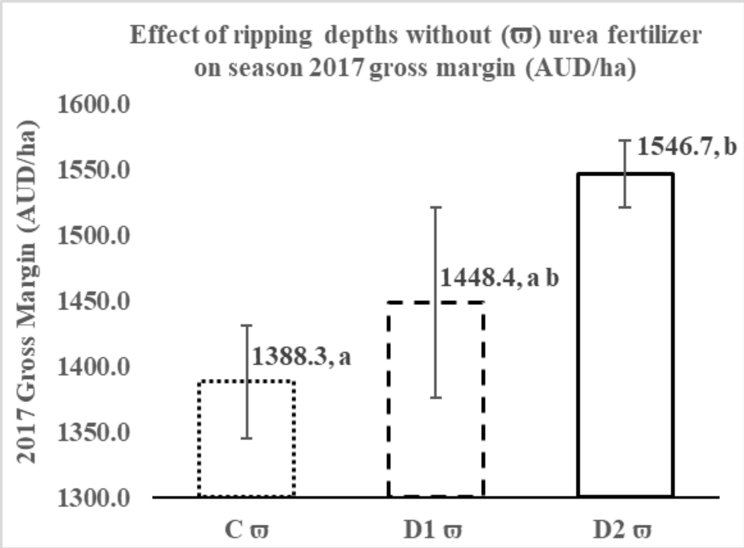
F.12.1 Analysis - Deep ripping effect



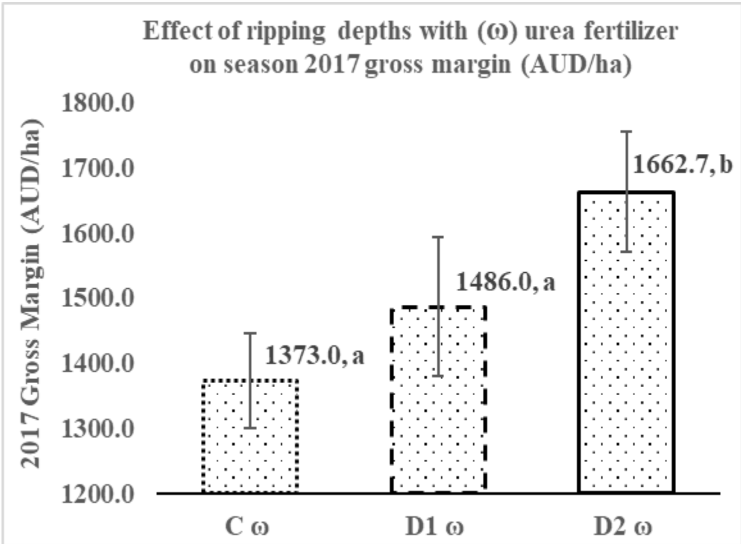
F.12.2 Analysis - Fertiliser rates effect



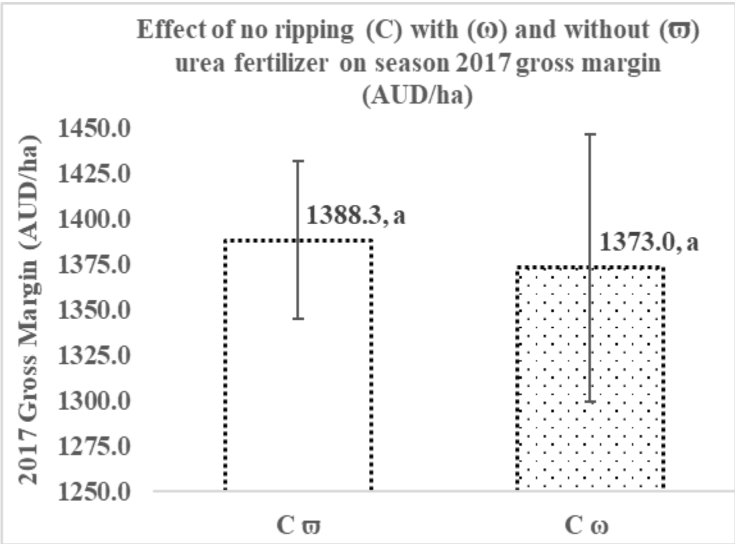
F.12.3 Analysis - Deep ripping with no fertiliser overlapping effect



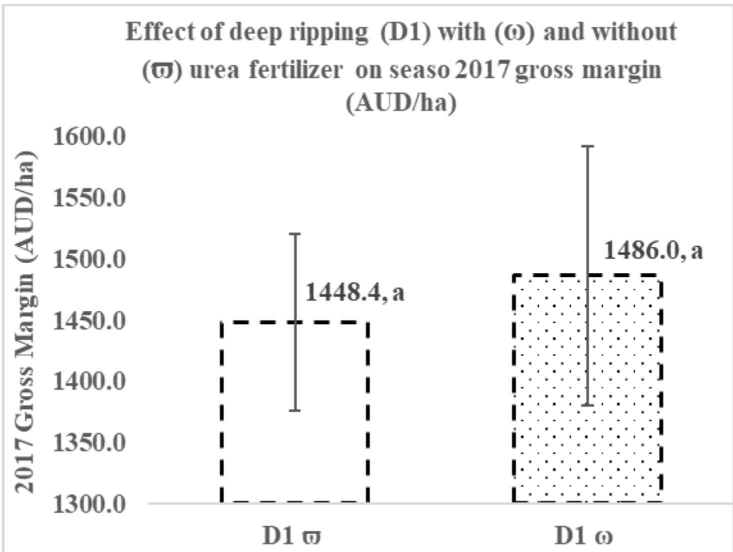
F.12.4 Analysis - Deep ripping with optimum fertiliser rates overlapping effect



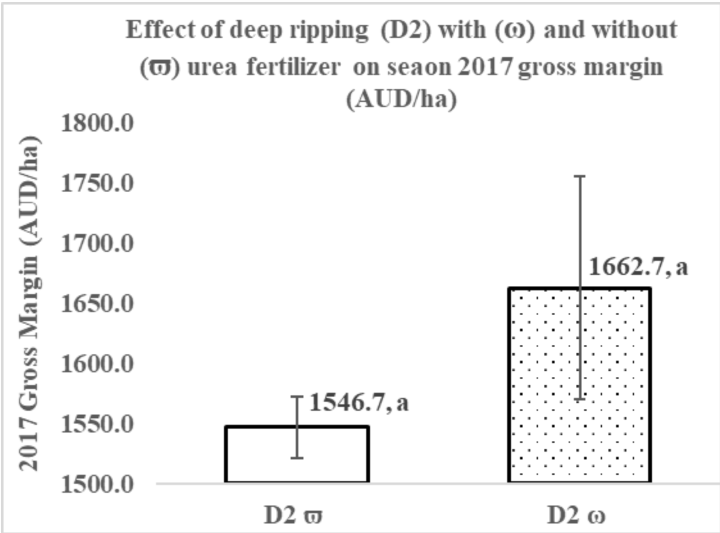
F.12.5 Analysis - Fertiliser rates with no deep ripping overlapping effect



F.12.6 Analysis - Fertiliser rates with D1 overlapping effect



F.12.7 Fertiliser rates with D2 overlapping effect



G. Crop performance modelling

G.1 Experiment season simulation (2017) - Ag plot

G.1.1 Sorghum grain yield

Site name	Ag plot				
Year	2017				
Crop	Sorghum				
Parameter	Observed grain yield		Simulated grain yield		Model error
Control (C)	4388		4221		- 3.8
D1	4964		4862		- 2.1
D2	5360		5284		- 1.4
(%) increase	C to D1	C to D2	C to D1	C to D2	
	13.1	22.1	15.2	25.2	

G.1.2 Sorghum dry biomass yield

Site name	Ag plot				
Year	2017				
Crop	Sorghum				
Parameter	Observed biomass yield		Simulated biomass yield		Model error
Control (C)	10950		8395		- 23.3
D1	12671		12064		- 4.8
D2	13269		12488		- 5.9
(%) increase	C to D1	C to D2	C to D1	C to D2	
	15.7	21.2	43.7	48.8	

G.1.3 Wheat grain yield

Site name	Ag plot			
Year	2017			
Crop	Wheat			
Parameter	Observed grain yield		Simulated grain yield		Model error
Control(C)	1828		1748		- 4.4
D1	2115		1973		- 6.7
D2	2419		2341		- 3.2
(%) increase	C to D1	C to D2	C to D1	C to D2	
	15.7	32.3	12.9	34	

G.1.4 Wheat dry biomass yield

Site name	Ag plot				
Year	2017				
Crop	Wheat				
Parameter	Observed biomass yield		Simulated biomass yield		Model error
Control (C)	4493		4302		- 4.3
D1	5380		5034		- 6.4
D2	5960		6081		+ 2
(%) increase	C to D1	C to D2	C to D1	C to D2	
	19.7	32.6	17	41.4	

G.2 Experiment season simulation (2018) - Evanslea

G.2.1 Sorghum grain yield

Site name	Evanslea				
Year	2018				
Crop	Sorghum				
Parameter	Observed grain yield		Simulated grain yield		Model error
Control (C)	6900		6251		- 9.4
D1	8100		7129		- 12.0
D2	7898		7078		- 10.4
(%) increase	C to D1	C to D2	C to D1	C to D2	
	17.4	14.5	14.1	13.2	

G.2.2 Sorghum dry biomass yield

<table>
<tr><td>Site name</td><td colspan="5">Evanslea</td></tr>
<tr><td>Year</td><td colspan="5">2018</td></tr>
<tr><td>Crop</td><td colspan="5">Sorghum</td></tr>
<tr><td>Parameter</td><td colspan="2">Observed biomass yield</td><td colspan="2">Simulated biomass yield</td><td>Model error</td></tr>
<tr><td>Control (C)</td><td colspan="2">12855</td><td colspan="2">11693</td><td>- 9.0</td></tr>
<tr><td>D1</td><td colspan="2">15369</td><td colspan="2">13364</td><td>- 13.0</td></tr>
<tr><td>D2</td><td colspan="2">15187</td><td colspan="2">13262</td><td>- 12.7</td></tr>
<tr><td rowspan="2">(%) increase</td><td>C to D1</td><td>C to D2</td><td>C to D1</td><td>C to D2</td><td></td></tr>
<tr><td>19.6</td><td>18.1</td><td>14.3</td><td>13.4</td><td></td></tr>
</table>

H. Sources used

H.1 Cost of subsoiling clayey soil

- Guide to machinery costs 2012/13: (http://www.nda.agric.za/docs/statsinfo/Guidemach1213.pdf),
- Guide to machinery costs 2013/14 (https://vdocuments.site/amp/guide-to-machinery-costs-201314.html),
- 2016-17 Farm Machinery Custom and Rental Rate Guide (https://dokumen.tips/amp/documents/2016-17-farm-machinery-custom-and-rental-rate-machinery-custom2016-17-farmmachinery.html),
- 2018-19 Farm Machinery Custom and Rental Rate (https://pubsaskdev.blob.core.windows.net/pubsask-prod/85808/85808-2018-19_Farm_Machinery_Custom_and_Rental_Rate_Guide.pdf),
- Ohio Farm Custom Rates 2018 (https://clinton.osu.edu/sites/clinton/files/imce/Ohio%20Farm%20Custom%20Rates%20Final%202018%20%28002%29.pdf),
- Estimating Farm Machinery Costs (Ag Decision Maker) (https://www.extension.iastate.edu/agdm/crops/html/a3-29.html)

  John Deere farm tractors by model (http://www.tractordata.com/farm-tractors/tractor-brands/johndeere/johndeere-tractors.html)
- Australian Institute of Petroleum (AIP) bulletins during experiments events (https://www.aip.com.au/pricing

H.2 Benefits of subsoiling clayey soil

H.2.1 Ag plot site

- Pacific Seeds Pty Ltd, Toowoomba
- AgMargins: Gross Margins Index
  https://www.agmargins.net.au/Reports/Index#
- Australian Crop Report, December 2018
  http://www.agriculture.gov.au/abares/Documents/AustCropRrt20181204_v1.0.0.pdf
- Farm Gross Margin and Enterprise Planning Guide, 2017
  http://pir.sa.gov.au/__data/assets/pdf_file/0008/235844/Farm_Gross_Margin_and_Enterprise_Planning_Guide_2018.pdf
- Index Mundi, 2017
  https://www.indexmundi.com/commodities/?commodity=urea&months=60&currency=aud
- Summer and winter crop gross margin budgets
  https://www.dpi.nsw.gov.au/agriculture/budgets/summer-crops
  https://www.dpi.nsw.gov.au/agriculture/budgets/winter-crops

H.2.2 Evanslea site

- Pacific Seeds Pty Ltd, Toowoomba
- Elders-Farm Supplies, Toowoomba.
- Index Mundi, 2018
  https://www.indexmundi.com/commodities/?commodity=urea&months=60&currency=aud
- Summer crop gross margin budgets
  https://www.dpi.nsw.gov.au/agriculture/budgets/summer-crops
- Agricultural Economic Insights
  https://aei.ag/2018/03/12/2018-fertiliser-prices-turn-higher/
  AgMargins: Gross Margins Index
  https://www.agmargins.net.au/Reports/Index#

H.3 APSIM model

H.3.1 The PAWC equations and its associated variables

- https://www.apsim.info/wp-content/uploads/2019/10/GRDC-Plant-Available-Water-Capacity-2013.pdf
- https://www.apsim.info/wp-content/uploads/2019/10/Soil-matters.pdf

H.3.2 Sorghum and Wheat Module Structure

- https://www.apsim.info/documentation/model-documentation/crop-module-documentation/