AGRONOMIC AND ECONOMIC PERFORMANCE OF ARABLE CROPS AS AFFECTED BY CONTROLLED AND NON-CONTROLLED TRAFFIC OF FARM MACHINERY

A thesis submitted by

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ABSTRACT

In mechanised agriculture, soil compaction occurs mainly as a result of traffic with heavy farm equipment. Compaction adversely affects the physical, chemical and biological properties of soils, and the ability of crops to efficiently use water (irrigation and rainfall) and nutrients, which therefore reduces crop yield and the amount of fertiliser recovered in grain.

This study was conducted to investigate the effect of traffic compaction on crop response to nitrogen (N) fertiliser and N use efficiency by replicating conditions representative of controlled (CTF) and non-controlled (non-CTF) traffic farming, respectively. The agronomic and economic performance of wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* (L.) Pioneer G22) were assessed in-field conditions over two consecutive seasons (2014-2015 and 2015-2016, respectively). The soil type at the experimental site is a well-drained Red Ferrosol (69% clay, 11% silt, and 20% sand). Three N fertiliser formulations, namely, urea (46% N), urea ammonium nitrate (UAN, 30% N, solution), and urea treated with 3,4-dimethyl pyrazole phosphate (ENTEC®, 46% N) were applied at rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1} N. Soil conditions (bulk density and strength) representative of CTF and non-CTF systems were achieved by first removing historical compaction using a subsoiler fitted with vertical, winged, tines operated at a depth of approximately 300 mm. A surface leveller was attached behind the tillage unit to smooth the surface in the same operation. Subsequently, six passes with a Belarus 920 tractor (100 HP, gross mass: 4 Mg) driven at a speed of 5 km h^{-1}, and fitted with 11.2-20 (front) and 15.5-38 (rear) tyres inflated to 0.24 and 0.18 MPa, respectively, were performed on the non-CTF soil. Given the vehicle available, this level of traffic

ensured that soil compaction conditions representative of non-CTF systems were achieved.

Soil physical and hydraulic properties were determined and results used to guide parametrisation of the Agricultural Production Systems Simulator (APSIM) model to enable long-term (115 years) prediction of traffic impacts on crop productivity and water use efficiency (WUE), and to quantify likely yield gaps in non-CTF relative to the controlled traffic farming (CTF) system.

For wheat, results showed that grain yield, total aboveground biomass, and harvest index were 12%, 9%, and 4% higher, respectively, in the traffic treatment representing CTF relative to that of the non-CTF system. For sorghum, grain yield was approximately 40% higher in the traffic treatment representative of CTF compared with that of the non-CTF treatment, and consistent with differences ($P<0.05$) in all measurements of crop yield components (total aboveground biomass, harvest index, and thousand-grain weight). Overall, there was no fertiliser type effect on grain yield, which was observed in both crops ($P>0.1$). This observation therefore confirmed that traffic compaction was the main factor affecting crop performance and the amount of N fertiliser recovered in grain.

Overall, agronomic efficiency (AE) and nitrogen use efficiency (NUE) calculations for wheat were greater in CTF by up to 35% and 40%, respectively, compared with the non-CTF treatment. For sorghum, AE and NUE calculations were both approximately 60% higher in the CTF treatment compared with non-CTF.

On average across the three fertiliser types the most economic rates of nitrogen (MERN) applied to wheat were 122 and 108 kg ha^{-1} N for CTF and non-CTF, respectively. The corresponding grain yields at these levels of N were 3337 and 2887 kg ha^{-1} for CTF and non-CTF, respectively (P-values <0.05). These differences in yield equated to agronomic efficiencies of 28 and 27 kg (grain) per kg N for CTF and non-CTF, respectively. Average MERN calculations for sorghum across all fertiliser types were 145 and 100 kg ha^{-1} N for CTF and non-CTF, respectively. The corresponding grain yields at these levels of N were 3430 and 1795 kg ha^{-1} for CTF and non-CTF, respectively (P-values <0.05). These differences in yield equated to agronomic efficiencies of 24 and 18 kg (grain) per kg N for CTF and non-CTF, respectively.

The results derived from the modelling work showed that in average rainfall years, yield reductions in non-CTF may be up to 13% and 38% for wheat and for sorghum, respectively, relative to the yields achieved in CTF. In below-average rainfall years, yield reductions in non-CTF can be up to 4% and 12% greater for wheat and sorghum, respectively, compared with the yield achieved in average rainfall years. In above-average rainfall years, differences in yield between CTF and non-CTF treatments were small, which showed that the effect of traffic compaction on crop yield is dependent on the seasonal effect of rainfall.

Modelled WUE and runoff were measured (sections 4.3.1 and 4.3.2, respectively) and were also significantly affected by compaction. For wheat, the simulated conditions of the CTF system reported up to 15% higher WUE compared with non-CTF (≈20.90 vs. 17.50 kg ha^{-1} mm^{-1} for CTF and non-CTF, respectively). For sorghum, WUE was 43% higher in CTF compared with the non-CTF treatment (≈8.40 vs. 4.80 kg ha^{-1} mm^{-1} for CTF and non-CTF, respectively). Modelled runoff increased proportionally with an increase in total rainfall, but it did to a significantly greater extent in non-CTF compared with CTF. Overall, modelled runoff volumes in wheat and sorghum were, respectively, 28% and 45% higher in non-CTF compared with CTF.

Given current price ratios (nitrogen-to-grain), and depending upon the fertiliser type used, gross margin penalties of approximately AUD50-70 and AUD110-190 per ha may be incurred in wheat and sorghum, respectively, when controlled traffic is not practised. This study also confirmed that N use efficiency cannot be significantly increased if the mechanisation system does not allow for avoidance of traffic compaction. Therefore, the agronomic, and possibly the environmental benefits associated with the use of enhanced efficiency fertiliser formulations may not be fully realised if soil compaction is not avoided. Improved soil structural conditions are, therefore, a pre-requisite for increased fertiliser use efficiency, crop productivity and sustainability.

THESIS CERTIFICATION PAGE

This Thesis is entirely the work of Mahmood Awad H. Hussein except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

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CONTRIBUTIONS TO THEORY AND PRACTICE FROM THIS RESEARCH

This project covered a relatively wide range of topics relating to dimensions of soil sustainability, farm economics and agricultural productivity, and in particular, to resource-use efficiency to the farm scale. A summary of the main contributions to theory and practice arising from this research include:

- This research brings about in-depth understanding of the yield-to-nitrogen fertiliser responses as affected by compaction, and in relation to traffic and tillage systems. Therefore, the differences in crop responses and fertiliser use efficiency were able to be quantified for both CTF and non-CTF.
- The research undertaken in this work has considered the fact that the fertiliser use efficiency cannot be increased by simply changing fertiliser rate and/or formulation if there is an underlying problem of compaction. Therefore, in order to improve nitrogen use efficiency, the soil condition also has to be (pre-requisite) improved.
- As growers progressively use enhanced efficiency fertilizer formulations (EEF), motivated by the need to mitigate emissions and reduce environmental losses, and in future comply with more stringent environmental regulations, this research provides the basic understanding of the likely performance of those formulations in two contrasting traffic systems.
- A novel modelling approach for simulating the long-term relationships between traffic compaction, crop productivity, water and fertiliser use efficiency was established using the Agricultural Production Systems Simulator (APSIM) model. Grain yields derived from this modelling study were in close agreement with data derived from field experimentation. Therefore, this modelling approach appears to be robust and may be used to assist further studies in this space and to assist decision-making.
- Based on the field experiments and modelling work, the research undertaken was also able to draw practical recommendations for land manages to increase input use efficiency. Areas that merit further research are discussed.

LIST OF RELATED PUBLICATIONS

JOURNAL (Submitted)

Hussein, M. A. H, Antille, D. L, Chen, G, Kodur, S, Tullberg, J. N, 'Controlled traffic farming improves nitrogen fertilizer use efficiency in wheat (*Triticum aestivum* L.): Field investigations and modelling', (Submitted) *European Journal of Agronomy*. **[Appendix A.1]**.

Hussein, M. A. H, Antille, D. L, Chen, G, Kodur, S, Tullberg, J. N, 'Controlled traffic farming improves nitrogen fertiliser use efficiency in sorghum (*Sorghum bicolor* L.): Field investigations and modelling', (Submitted) *Experimental Agriculture.* **[Appendix A.2].**

CONFERENCE PROCEEDINGS

Hussein, M. A. H., Antille, D. L., Chen, G., Luhaib, A. A. A., Kodur, S., Tullberg, J. N. (2018). Agronomic performance of sorghum (*Sorghum bicolor* L. Moench) and fertilizer use efficiency as affected by controlled and non-controlled traffic of farm machinery. ASABE Paper No.: 1800250. St. Joseph, Mich.: ASABE. DOI: 1013031/aim.201800250.

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

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

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Luhaib, A. A, Chen, G, Tullberg, J. N, **Hussein, M. A. H.** 2017. Controlled traffic farming reduces energy requirements in Australian cropping systems. *The First MoHESR and HCED Iraqi Scholars Conference in Australasia 2017*, pp 360-367. http://www.iraqischolars-isca2017.org/files/proceedings_ISCA2017.pdf

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ABBREVIATIONS

ABARE:	Australian Bureau of Agricultural and Resource Economics
ABS:	Australian Bureau of Statistics
ACCC:	Australian Competition and Consumer Commission
ACTFA:	Australian Controlled Traffic Farming Association
AE:	Agronomic efficiency
AER:	Australian Energy Regulator
ANOVA:	Analysis of variance
APES:	Agricultural Production and Externalities Simulator
APSIM:	Agricultural Production Systems Simulator
AUD:	Australian Dollar
BD:	Bulk Density
BOM:	Bureau of Meteorology
°C:	Degree of Celsius
CA	Conservation agriculture
C_F:	Cost of fertiliser
CROPSYST:	Cropping Systems Simulation
C_S:	Cost of seeds
CTF:	Controlled Traffic Farming
DAISY:	Danish Simulation Model
DAP:	Di-ammonium Phosphate
DMPP:	Dimethyl pyrazole phosphate
DSSAT:	Decision Support System for Agro-technology Transfer
DUL:	Drained Upper Limit
EC:	Electrical Conductivity
FAO:	Food and Agriculture Organisation
FASSET:	Farm Assessment Tool
FIFA:	Fertilizer Industry Federation of Australia
FUE:	Fertiliser use efficiency
GHG:	Greenhouse Gas
GI:	Gross income
GM:	Gross margin
HI:	Harvest index
I_t:	Infiltration rate
K_{SAT}:	Saturated Hydraulic Conductivity

LL:	Lower Limit
$LSD_{[5\% level]}$:	Least significant differences (5% level)
MAP:	Mono-ammonium phosphate
MERN:	Most economic rate of nitrogen
N uptake:	Nitrogen uptake
N:	Nitrogen
NT	No-tillage
$NH_3^- - N$:	Ammonia Nitrogen
$NH_4^+ - N$:	Ammonium Nitrogen
NO_3^-:	Nitrate
n:	Number of observations
N_2O:	Nitrous oxide
N_{Rate}:	Nitrogen application rate
NUE:	Nitrogen use efficiency
OCC	Office of Climate Change
P_2O_5:	Phosphate
P_C:	Price of crop
P_N:	Price of nitrogen
R_P:	Price ratio
SAT:	Saturated
Std.:	Standard Deviation
SE:	Stander Error
SO_3:	Sulphur trioxide
SPR:	Soil penetration resistance
SPSS:	Statistical Package for the Social Sciences
SSP:	Single Superphosphate
STICS:	Simulator Multidisciplinary pour les Cultures Standard
TGW:	Thousand grain weight
TN:	Total Nitrogen
TVC:	Total variable costs
UAN:	Urea Ammonium Nitrate
WOFOST:	World Food Studies
WUE:	Water use efficiency
ZT:	Zero-Tillage
ΔTT:	Daily thermal time

CHAPTER 1: INTRODUCTION

1. INTRODUCTION

1.1. Project description

The global demand for food, fibre and energy is set to increase in response to the continuous growth of the world population (Godfray et al., 2010). Recent estimates suggested that the global population will increase from approximately 7.2 billion at present to between 9 and 10 billion in 2050 (FAO, 2013; Gerland et al., 2014). This will result in increased demand on soil resources as well as improved input-use efficiency (Lal, 2008; Norton et al., 2014), which will require a high rate of adoption of best-recommended management practices for soil and crop. Several studies (e.g., Van den Akker and Canarache, 2001; Hamza and Anderson, 2005; Houšková and Montanarella, 2008) have indicated that traffic-induced soil compaction is one of the main causes of soil degradation worldwide. In this regard, controlled traffic farming (CTF) systems offer an effective means to manage soil compaction, in addition to other agronomic and environmental benefits (Li et al., 2007, 2008; Vermeulen and Mosquera, 2009; McPhee et al., 2015). The Australian Controlled Traffic Farming Association Inc. (ACTFA, https://www.actfa.net/) defines controlled traffic farming (CTF) as a system in which:

- All farm machinery has the same or modular working and track gauge width so that field traffic can be confined to the least possible area of permanent traffic lanes,
- All machinery is capable of precise guidance along those permanent traffic lanes, and
- Permanent traffic lanes layout is designed to optimise surface drainage and logistics **(Figure 1.1)**.

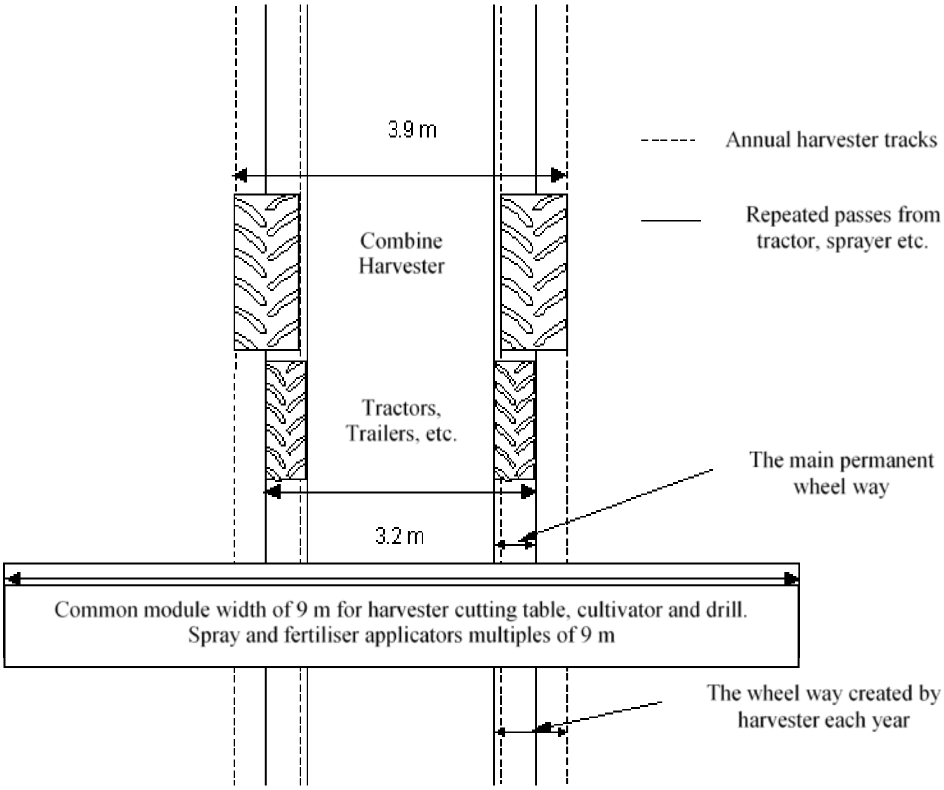


Figure 1.1. Common track-width module for different tires of tractor, sprayer, trailer and harvester (Chamen et al, 2003).

Recent studies (e.g., Antille et al., 2015a) have shown that CTF systems have the potential to either reduce nitrogen (N) fertiliser inputs without compromising crop yield or increase crop yield for given fertiliser input. This is supported by studies showing enhanced structural conditions in soils established under CTF (e.g., McHugh et al., 2009) and by enhanced nutrient uptake in the absence of traffic compaction (e.g., Lipiec and Stępniewski, 1995).

In well-designed CTF systems in Australia, the area subject to traffic typically occupies 15% (or less) of the cultivated field area, particularly when permanent no-tillage is practised. By contrast, in non-CTF systems, this area is often greater than 45% and it can be as high as 85% in conventional tillage systems that require primary tillage operations prior to crop establishment (Tullberg et al., 2007; Kroulík et al., 2009). Widespread compaction, resulting from disorganised traffic patterns with agricultural machinery, also has considerable implications on nutrient use efficiency and nutrient losses to the environment. These may be through enhanced runoff (overland flow) and gaseous evolution, and consequently, crop yield and economic return from applied fertiliser. This is an important consideration given the trend that has occurred in the last decades towards the use and development of heavier machines (Kutzbach, 2000; Chamen, 2015), which therefore reinforces the need to confine all field traffic to the least possible area of permanent wheel-lanes.

The need for increased food production to sustain an ever growing population will increase the reliance on fertiliser inputs (Dawson and Hilton, 2011). Avoidance of traffic compaction through the adoption of CTF systems has the potential to either reduce nitrogen (N) fertiliser inputs without compromising crop yield or increase crop yield for a given fertiliser input.

Currently, about 40% of the human population relies on nitrogen (N) fertiliser for food production (Balasubramanian et al., 2004). Application of fertiliser in excess of crop requirements impacts on economic return and use efficiency leading to increased environmental losses (Barłog and Grzebisz, 2004). The 4R's principle (right place, right time, right rate and source) is suggested as the best management practice for fertiliser use on crops (Snyder et al., 2009; Norton et al., 2014). However, 'good' soil structural conditions are also needed to maximise water and nutrient exploitation by plant roots and subsequent conversion into crop biomass and yield (Li et al., 2008).

The conclusions derived from the literature review conducted indicated that most studies have focused on the effect of soil compaction on nutrient uptake, nutrient losses such as gaseous emissions and loss of crop yield. However, there appears to be a paucity of information concerning the effects of compaction induced by the traffic of farm machinery on the actual yield-to-fertiliser response curve from which optimum economic rates can be derived. This study has investigated the effects of soil compaction caused by field traffic on fertiliser-use-efficiency and crop yield, and determined potential impacts on crop gross margins by comparing the performance of crops grown under simulated random and controlled traffic conditions. Several studies (e.g., Barber, 1997; Bouwman et al., 2002; Barłog and Grzebisz, 2004; Bolson and Kaleita, 2007; Bowman, 2008; Botta et al., 2010; Boyer et al., 2010) have investigated soil compaction in relation to fertiliser management practices. However, there appears to be a lack of information regarding the effect of traffic systems on fertiliser-use efficiency and crop yield-to-nitrogen responses for edapho-climatic conditions representative of subtropical environments.

This work also seeks to demonstrate that in terms of nitrogen (N) use efficiency (NUE) little can be gained from the use of enhanced fertilizer formulations if soil is affected by traffic compaction so that crop agronomic performance cannot be optimized. This has practical implications for N management as much effort is being spent on investigating the role of enhanced efficiency fertilizer formulations (EEF) in increasing NUE and mitigating greenhouse gas emissions (e.g., Antille, 2018; Antille et al., 2018), but little consideration has been given to the detrimental effects of traffic compaction, with some exceptions (e.g., Tullberg et al., 2018). The experimental data obtained from this project (soil physical and hydraulic properties) were used to parameterise the model in order to quantify likely long-term impacts of traffic systems on crop productivity based on published approaches for simulating the effect of crop performance. To achieve this, the Agricultural Production Simulator (APSIM) (Keating et al., 2003; Holzworth et al., 2014) was used to predict the likely effects of traffic compaction on water-use efficiency, runoff and crop performance of winter wheat and sorghum, which are the most common crops in southern Queensland.

1.5.1. Aim

The overall aim of this research was to determine the effects of controlled and non-controlled traffic of farm machinery on the agronomic and economic performance of arable crops subjected to varying fertiliser formulations and nitrogen application rates.

1.5.2. Objectives

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

1. Determine the effects of traffic compaction on the yield-to-nitrogen response relationship of winter wheat and sorghum crops for a range of nitrogen fertiliser formulations,
2. Determine the effect of such compaction on fertiliser nitrogen-use efficiency to be able to quantify differences between controlled and non-controlled traffic farming systems,
3. Collect soil and crop data to enable parameterisation of the Agricultural Production Systems Simulator (APSIM) model (Keating et al, 2003; Holzworth et al 2014) to aid the development of yield functions that capture the effects of nitrogen fertilisation and traffic compaction on crop production, water-use efficiency and runoff,
4. Conduct technical-economic analyses to quantify the effects of traffic-induced soil compaction on crop gross margin and economic return from fertiliser used on crops, and to assess the most economic rate of nitrogen for both traffic systems, and

5. Develop a set of practical recommendations to improve crop, soil and fertiliser management practices.

1.2. Outline of methodology

The project was sub-divided into four stages (**Sections 1.2.1 to 1.2.5**) in order to achieve the research aim and the objectives defined in the previous section. Every single stage will partially contribute to the achievement of the objectives and the overall aim of the research.

1.5.1. Stage I

Developing an understanding of the research and the effects of soil compaction induced by the traffic of farm machinery on fertiliser input and yield production were included at this stage. Therefore, a literature review was required to identify the research gap and define the aim and objectives of this research. The literature review has also demonstrated the effects of traffic compaction on crop performance and input use efficiency, and that has helped to establish the methodology of the experiments of this project. The following aspects were also taken into account in stage I:

- Identification of the cropping area, soil types and climate in Australia with more focus on Queensland,
- A brief analysis of the fertiliser market and demand in Australia, and an overview of the fertiliser commonly used in cereal crops especially regards to wheat and sorghum,
- Understanding the direct effects of soil compaction on crop production and fertiliser use efficiency, and the indirect impacts on the environment (e.g. greenhouse gas emissions), and

- Overview of the modelling of crop performance with especial regard to Agricultural Production System Simulator (APSIM) model.

As a result, objective number one of this project was defined and three fertiliser types with different nitrogen concentrations were suggested. These types of fertiliser were used: urea (46% N), urea treated with 3,4-dimethyl pyrazole phosphate (DMPP), commercially known as ENTEC® urea (46% N), and urea ammonium nitrate referred to as UAN (30% N, solution). All fertiliser treatments, including controls, were set up in triplicate (n=3). The nitrogen fertiliser rates have been explained in the following stages.

Based on earlier studies (e.g., Lipiec et al., 2003; McHugh et al., 2009), it can be stated that structural condition in soil and nitrate uptake can be enhanced in the absence of traffic compaction. Two soil conditions (bulk density) representative of controlled and non-controlled traffic farming systems were used as follows:

- Non-compaction conditions to represent controlled traffic farming (CTF) system, (achieved by removing compaction through subsoiling to a depth of 300 mm)
- Compaction conditions to represent non-controlled traffic (non-CTF) system (achieved by performing a total of six overlapped passes to achieve the desired density given the equipment (tractor) and soil condition at the time traffic compaction was imposed).

The following parameters were also determined at this stage:

- Maximum dry bulk density,
- Optimum water content,
- Total nitrogen in the soil,
- Soil organic matter,

- Soil $pH_{1:5}$ (soil: water extract),
- Electrical conductivity,
- Soil mineral nitrogen ($NO_3^- - N$, $NH_4^+ - N$),
- Soil particle size analysis (clay, silt, sand).

1.5.2. Stage II

This stage consisted of developing the methodology and conducting the experimental work in relation to objectives number one and two of the project. An investigation into the effect of traffic compaction on the yield-to-nitrogen response of winter and summer crops was undertaken at this stage. In addition, it investigated the effect of such compaction on fertiliser-use efficiency and quantified differences between CTF and non-CTF systems. The study was conducted as follows:

Field studies: The experiments were conducted at the Experimental Station of the University of Southern Queensland (27°36'35.27"S, 151°55'50.62"E) located in Toowoomba (Queensland, Australia) during the winter of 2015 (June-November) and summer of 2015-2016 (November-March) on winter wheat (*Triticum aestivum* L.), and sorghum crop (*Sorghum bicolor* L.), respectively.

Nitrogen fertiliser (mentioned in the previous stage) were hand-applied in a single band (≈50 mm) next to the plant row and incorporated at N rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1}. The applications of N fertiliser were split into two halves (50% each) for the rates of 200 and 300 kg ha^{-1}.

i. Soil measurements and analyses

- Soil bulk density,
- Cone penetrometer resistance,
- Soil moisture content,

- Hydraulic conductivity,
- Soil water infiltration.

ii. Crop measurements

- Grain yield,
- Total aboveground biomass,
- Harvest index,
- Thousand grain weight,
- Nitrogen uptake,
- Nitrogen use efficiency.

1.5.3. Stage III

The third stage consisted of developing the methodology in relation to objective number three of this research. Long-term impacts of crop performance were assessed using the Agricultural Production Systems Simulator (APSIM). The following factors were studied in both of the simulated CTF and non-CTF systems.

- Grain yield,
- Total aboveground biomass,
- Runoff,
- Water use efficiency,
- Sowing soil moisture.

1.5.4. Stage IV

This stage consisted of developing the methodology in relation to the fourth objective of this research. The main target of this stage was to integrate the results from the experimental work conducted in **Stage II (Section 1.3.2)** and the management and economic aspects of this study. The experimental data that included agronomic and technical-economic aspects of the work was integrated. Based on the fertiliser and grain prices, the price ratios and the non-linear equation used by James and Godwin (2003), the economic parameters were as follows:

Economic measurements

- Most economic rate of nitrogen (MERN),
- Crop gross margin (GM),
- Sensitivity analysis

Finally, the main outcomes coming from this research were summarised and the overall conclusions were drawn. Recommendations for future research in this field were also made.

1.3. Statistical analyses

The Statistical Package for the Social Sciences (SPSS-version 23) software was used to analyse the experimental data (Swan and Sandilands 1995) and involved the analysis of variance (ANOVA). Means of cone index were compared for significance using the least significant differences (LSD) at 5% level of probability, and using Duncan for the rest of means data at the same level of probability. Statistical analyses were graphically assessed by means of residual plots and normalisation of data was not required. Yield-to-nitrogen responses were investigated by means of nonlinear (quadratic) regression analyses. Linear and Nonlinear regression analyses were used to describe the relationships between nitrogen-use-efficiency and N application rates, from which nitrogen-use-efficiency and agronomic efficiency corresponding to the most economic rate of nitrogen (MERN) were derived. Analytical values are reported as the mean ± standard deviation (Std.).

1.4. Thesis structure

A summary of the methodological approach and the thesis structure is shown in **Figure 1.2**. After this introduction to the research **(Chapter 1)**, a literature review is presented in **Chapter 2** which concentrates on the traffic systems and crop responses to fertiliser management. Furthermore, it demonstrates the effect of soil compaction on crop production and input-use efficiency. Crop models are also discussed in this chapter in relation to the Agricultural Production System Simulator (APSIM) model. Field studies and the practical experiments and their corresponding methodologies, results and discussion are **Chapter 3**. **Chapter 4** demonstrates the long-term effects of the two traffic systems by modelling of crop performance using APSIM. **Chapter 5** focuses on the economic analysis of the crop response to applied fertiliser and soil compaction. Special emphasis has been placed on the effect of the use of urea ammonium nitrate, ENTEC® urea and urea on a crop's gross margins. The integrated discussion is presented in **Chapter 6** (overall discussion). The overall conclusions of the main finding resulting from the individual experiments are presented in **Chapter 7**. A number of practical recommendations are provided in **Chapter 8**.

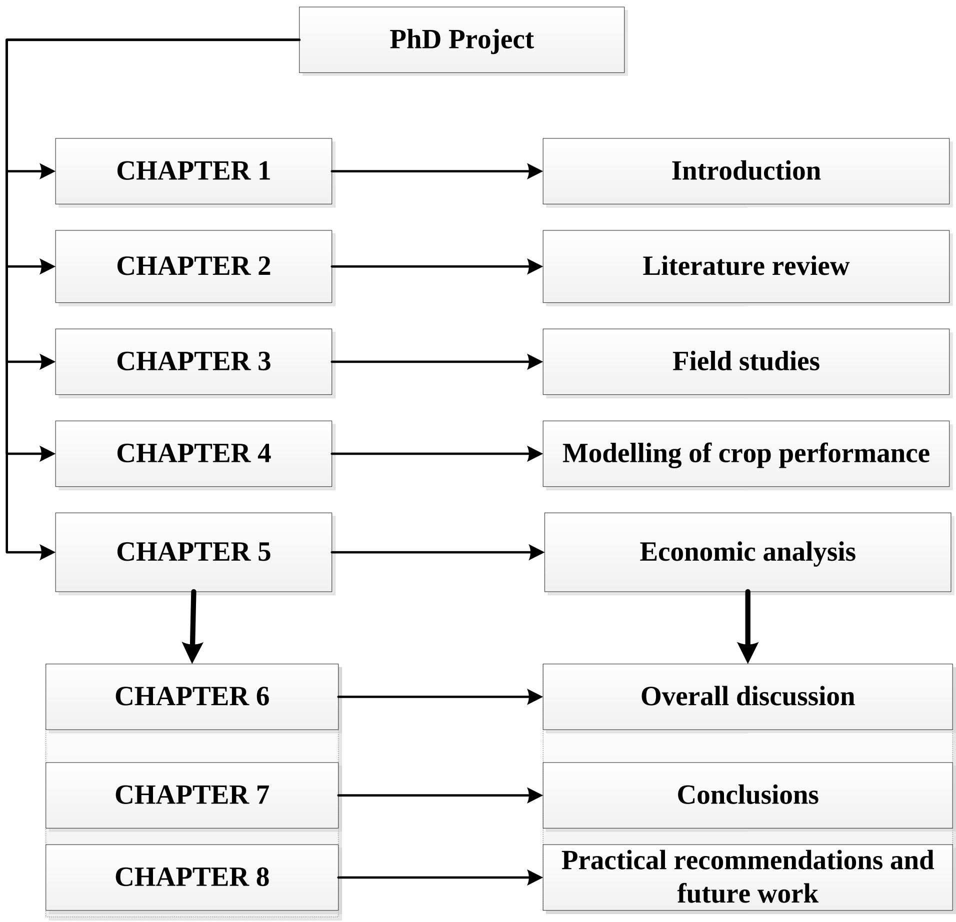


Figure 1.2. Outline of the research methodology and summary of the thesis structure

CHAPTER 2: LITERATURE REVIEW

2. LITERATURE REVIEW

2.1. Introduction

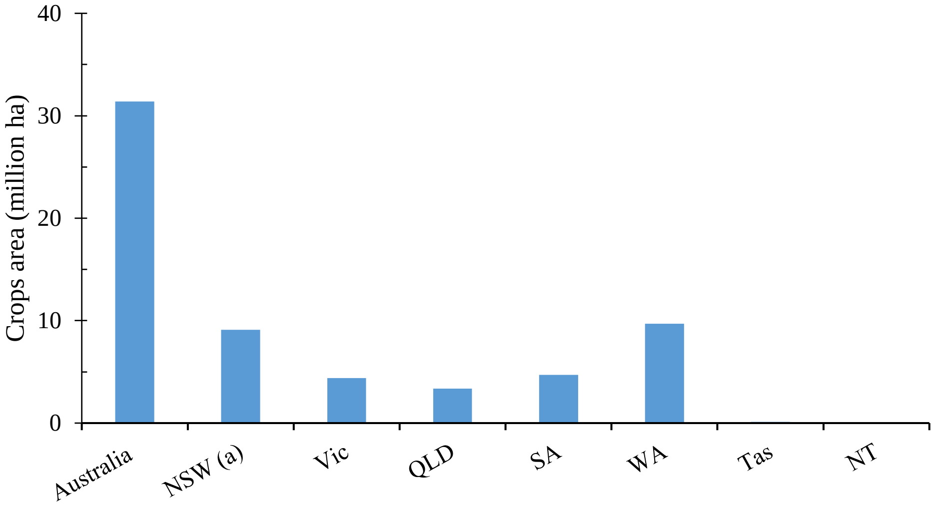
The main objective of this chapter is to review existing available knowledge on the traffic systems on farms and the relationship between soil compaction and fertiliser use efficiency. Based on the objectives and the aim of the research listed in **Chapter 1**, the review, therefore, has three main sections in the context of soil compaction induced by the traffic of farm machinery and its effects on:

- Crop responses to soil compaction
- Nitrogen fertiliser use efficiency
- Farm profitability.

The aim of this chapter is to bring together and draw conclusions from research targeted at understanding the impact of field traffic on soils, fertiliser-use efficiency and crop responses. The first section of the literature review examines current land use within the grain industries in Australia. The following section describes the climate and soil resources in a study area (South East Queensland). The third part of this chapter (**Sections 2.4-2.7**) focuses on fertiliser management and nutrient dynamics in agricultural systems with particular regard to nitrogen, and its effects on crop production. Tillage and traffic systems are discussed in **Section 2.8**, with their effects on crop production, soil characterisations, and economic and environmental considerations. **Section 2.9** examines crop modelling with particular regard to the Agricultural Production Systems Simulator (APSIM). The main sections mentioned above concluded in **Section 2.10** to highlight the research gaps that will be studied further in the following chapters.

2.2. Overview of the grain industry in Australia

In spite of Australia's generally harsh environment, including its unpredictable weather, agriculture is the most extensive form of land use. Based on information from the Australian Bureau of Statistics (ABS, 2016), in 2014-15 there were approximately 385 million hectares of land owned or operated by 123000 agricultural businesses in Australia. These estimates represent a reduction in land area of 22 million hectares, or 5.3%, and a 5400, or 4.2%, reduction in the number of agricultural businesses compared to the 2013-14 season. The area under crops in Australia decreased by 2.8%, (from 32 to 31 million hectares) in 2014-15 compared to the previous season (**Figure 2.1)**. The largest decrease occurred in South Australia, which declined by 258,000 hectares, or 5%, in the same period. In contrast, Tasmania reported a 5,000 hectare or 4% increase in land used for crops. Around 30% of all Australian farms produced grains, oilseeds and pulses in 2015-16 (ABS, 2016).



(a) Includes Australian Capital Territory.

Figure 2.1. Land used mainly for crops during 2014-15 (ABS, 2016)

The grain industry makes an important contribution to the Australian economy. In 2015-16, production of grains, oilseeds and pulse crops accounted for approximately

23% (AUD 13 billion) of the total gross value of farm production and about 24% of the total value of farm export income (Martin, 2016).The history of the wheat and sorghum industry in Australia and particularly in Queensland is reviewed to provide a background for the importance of these two crops in both the nation and this particular state. Wheat is the most important individual crop by tonnage and value in Australia. Approximately 14 million hectares of wheat are planted annually, which represents more than half of Australian cropland (Doyle, 2001; Hochman, et al., 2013). The historical wheat production in Australia and the areas that are occupied by wheat are shown in **(Figure 2.2)**. In 2015–16 the gross value of farm production (GVP) for wheat was around AUD 6 billion, almost half of total GVP for the grains industry (Martin, 2016). Total production of wheat in 2015–16 was around 22 million tonnes or 56% of total grains industry tonnage (ABARES, 2017).

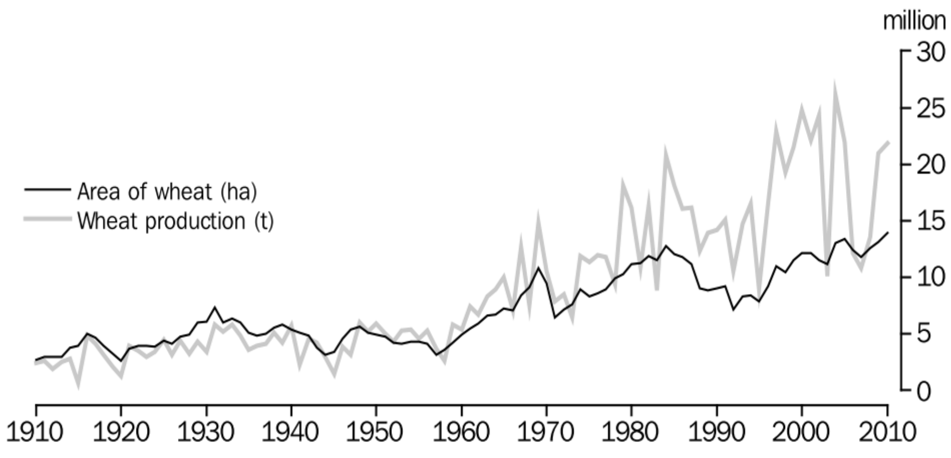


Figure 2.2. Wheat production in Australia and the area planted with wheat from 1910 to 2010 (Source: ABS, 2011).

Wheat is produced in all States but primarily on the mainland in a narrow crescent known as the 'wheat belt'. The wheat belt stretches in a curve from central Queensland through New South Wales **(Figure 2.3)**, Victoria and South Australia. In Western

Australia, the wheat belt continues around the south-west of the state and some way north, along the western edge of the continent (ABS, 2012).

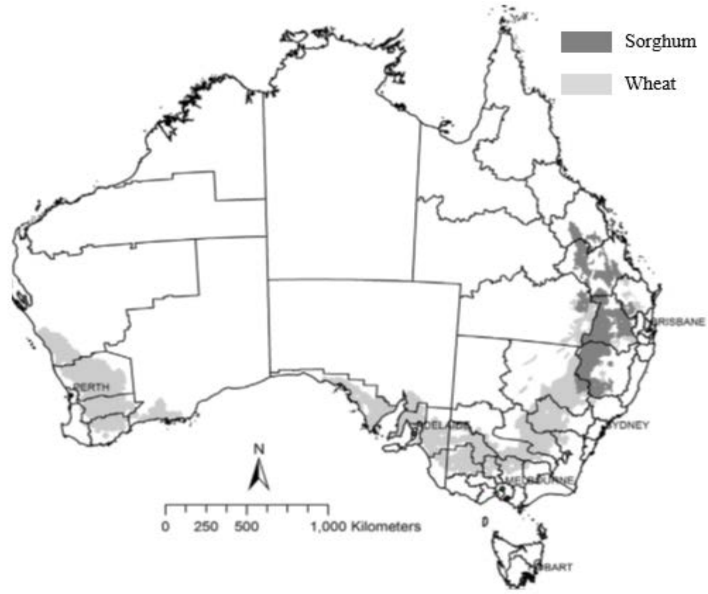


Figure 2.3. Map of the wheat (light grey) and sorghum (dark grey) cropping regions of Australia. Wheat is also grown within the sorghum region (Potgieter et al., 2016).

The statistics in the ABS (2013), indicated that in 2012-13, approximately 14 million hectares were planted with wheat in Australia to harvest 22 million tonnes. Western Australia planted and harvested the most wheat followed by New South Wales and South Australia **(Figure 2.4)**. The total area of Queensland (QLD) is 173 million hectares, of which 130 million hectares are used for agricultural activities, representing approximately 75% of the total state land area. Land-use for cropping in Queensland has remained relatively stable for the past 30 years, fluctuating between 1.5 and 3.5 million hectares.

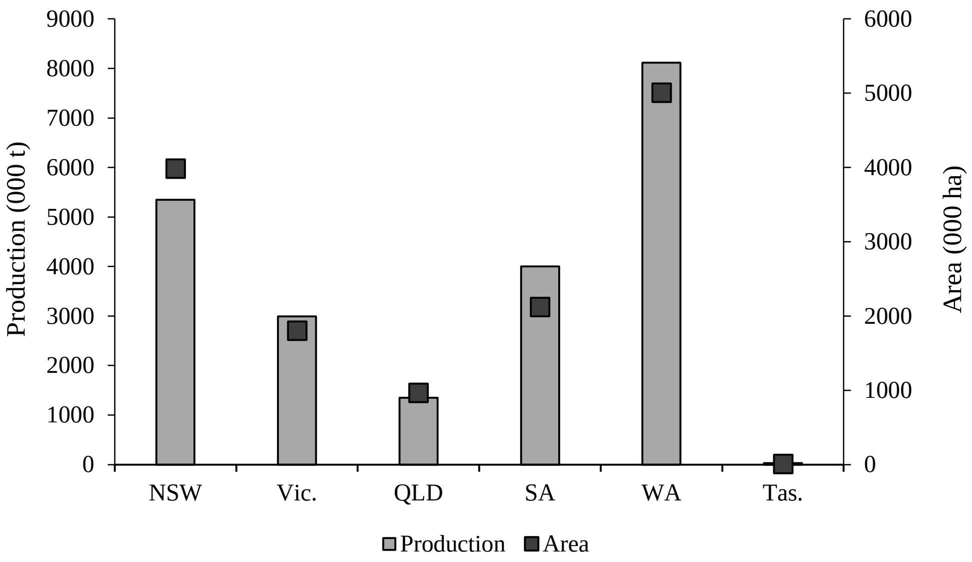


Figure 2.4. Wheat production and area by state and territory at the harvested season of 2013 (Source: ABS, 2013).

The major crops that are usually planted in QLD in descending order are wheat, sorghum, sugarcane, cotton and barley (ABS, 2016). Wheat occupies around 42%, while sorghum occupies approximately half the amount of land under wheat **(Figure 2.5)**. Wheat production in Queensland is estimated to have increased by 40% in 2017-2018 to around 2 million tonnes, despite a 5% reduction in planted area (ABARES, 2017). On a commodity basis, wheat (*Triticum aestivum* L.) is the most widely grown crop in the QLD, which contributes about AUD 5 billion (ABS, 2012) to the gross value of production.

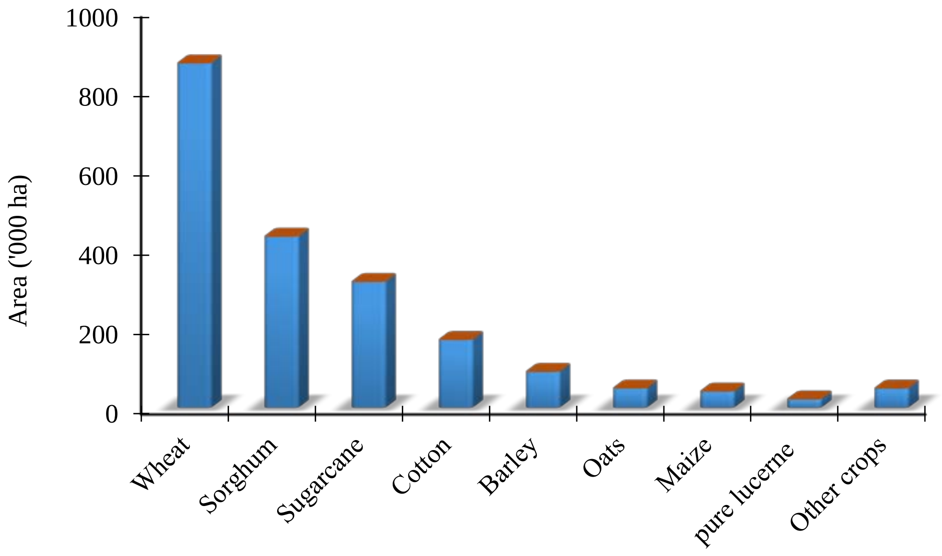


Figure 2.5. Area ('000) occupied by main crops in Queensland during the season of 2015 (ABS, 2016).

Average wheat production per hectare in Queensland ranged from 1.2 to 2 t ha^{-1} during the last 10 years. The season of 2008-2009 produced the highest yield value (2 t ha^{-1}) during this particular season **(Figure 2.6)**. Similarly, around 1.6 million tonnes were harvested from 865,000 ha in the harvest season of 2012-13 (ABS 2013).

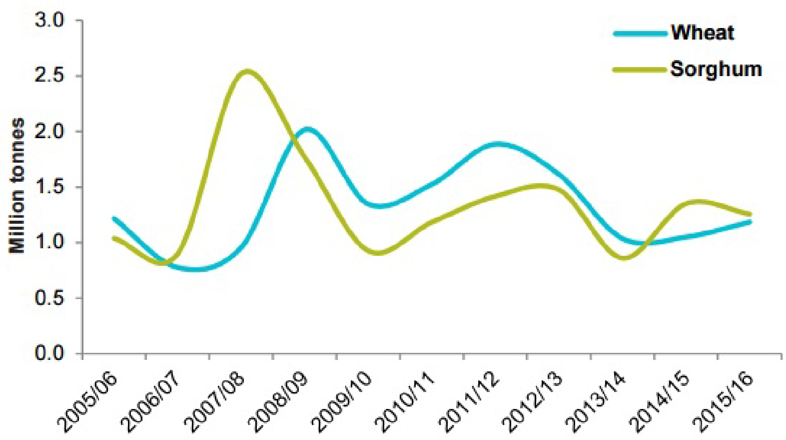


Figure 2.6. The production of wheat in Queensland from 2005 to 2016 (ABARES, 2016).

CHAPTER 2: LITERATURE REVIEW

Sorghum is an important part of the cropping system and farm economy in Australia. The trend in sorghum yield in Australia has been consistent and positive over the last 30 years, while yield trends for other cereals like wheat, maize and rice have slowed. Grain sorghum is grown in north-eastern Australia, and also this crop is often grown in rotation with winter cereals such as winter wheat in some areas (**Figure 2.4**). Sorghum is the major dryland crop grown in the north-eastern cropping zone of Australia (Pratley, 2003). According to the most recent statistics, sorghum is planted in Australia over approximately 500,000 ha. During 2012–13, Australia produces approximately two million tonnes, grown in significant quantities in Queensland and northern New South Wales (ABS, 2012).

The production of sorghum has ranged from as low as 1.3 million tonnes to a record high of 2.7 million tonnes in the seasons of 2006/2007 and 2008/2009, respectively (Potgieter et al, 2016). However, due to higher expected returns from growing cotton, the area planted to sorghum in Queensland is forecast to fall by 40% in 2017-2018 to 300,000 hectares, with 45% reduction in the production of sorghum (ABARES, 2017).

Most regions in Australia are not able to produce two crops (two seasons) in one year, however, the Darling Downs is a region where grain growers are able to produce a diverse range of summer and winter crops annually due to its favourable climate and soils (PWC, 2011) as they are the essential resources for the plant during its lifetime (Gregorich et al., 2011).

The demand for maize in Australia is more than 400 kt year^{-1} whereas production is about 360 kt year^{-1}. An appreciable amount of the maize demand is currently met by rainfed (52%) and irrigated (40%) production systems in Victoria, Queensland, and New South Wales, which account for 2%, 54% and 43%, respectively, of the total maize area of maize in Australia (Chauhan et al., 2013). In Queensland and northern

New South Wales (NNSW), which grow about nearly 90% of maize under rainfed conditions, the average yield is <5 t ha^{-1} (ABARE, 2006).

Australian rice is only 0.2% of world production but exports (80% of the rice produced) are more than 4% of world trade. Australian rice varieties (for example *Japonica*) are different to those grown in monsoonal wetland countries such as Thailand and Indonesia and were specially developed to suit the hot and dry conditions of southern NSW (Mushtaq et al., 2014). Australia has one of the highest average yields of rice (10 t ha^{-1}) in the world and over the past thirty years there have been substantial increases in irrigation and total water productivity (RGA, 2011).

2.3. Climate

The South East Queensland (SEQ) region has a sub-tropical climate influenced by tropical systems from the north and fluctuation in high-pressure ridges to the south. Rainfall is distributed unevenly throughout the year, with up to 65% falling during the summer months (October to March). The winter and spring months (between July and September) are often the driest. The total rainfall varies from 650 mm in western districts to 1000 mm in the eastern districts (**Figure 2.7**). Air temperature records for the last three decades show that mean monthly maximum and minimum temperatures were 27.1°C (range: 33.1 C° in January to 19.8 C° in June) and 12.1°C (range: 19.5 C° in January to 4.8 C° in August), respectively (BOM, 2017).

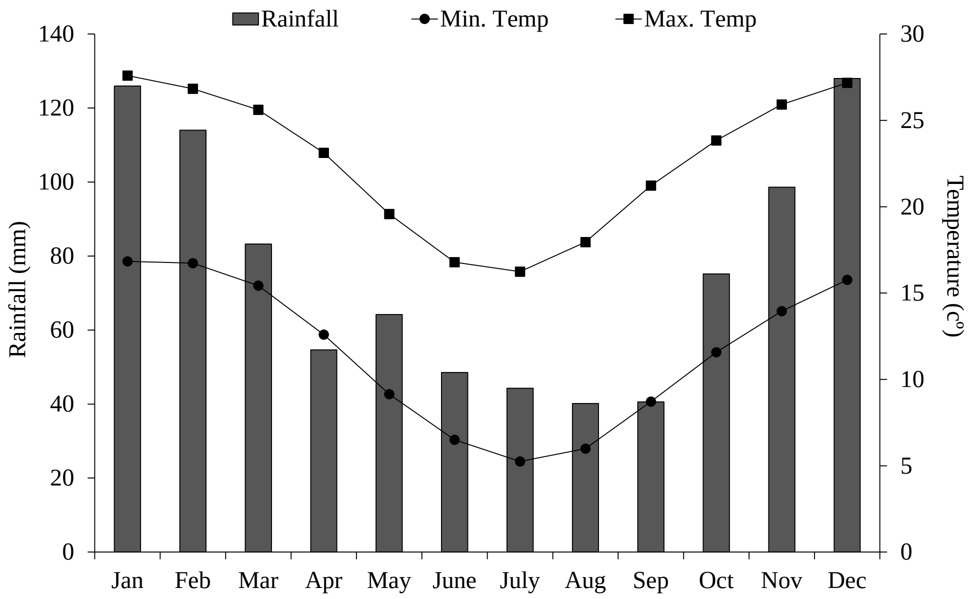


Figure 2.7. Monthly rainfall (mm), maximum and minimum temperatures for long-term (1970-2016), records for Toowoomba, QLD, Australia (BOM, 2017).

The Department of Environment and Resource Management released a report in 2010 titled 'Climate change in Queensland'. The report concluded that the winter rainfall for SEQ had declined substantially since the middle of the last century. The largest proportional decline was in early winter (May-July). In particular, a sudden drop-off in winter rainfall in the range of 15-20% was observed in the mid-1970s. This report also indicates that in future much of Queensland will be drier; however, it is likely that the occurrence of intense rainfall events will increase in summer. The average temperatures are also projected to increase by 0.6-1.5 ˚C by 2030. An increase in the amount of greenhouse gas emissions can be attributed to climate change. The changes were simulated by the Office of Climate Change (OCC, 2009) using two scenarios (low and high gas emissions) to predict the changes in annual temperature (°C), rainfall (%) and potential evapo-transpiration (%) by 2050 (**Figure 2.8**).

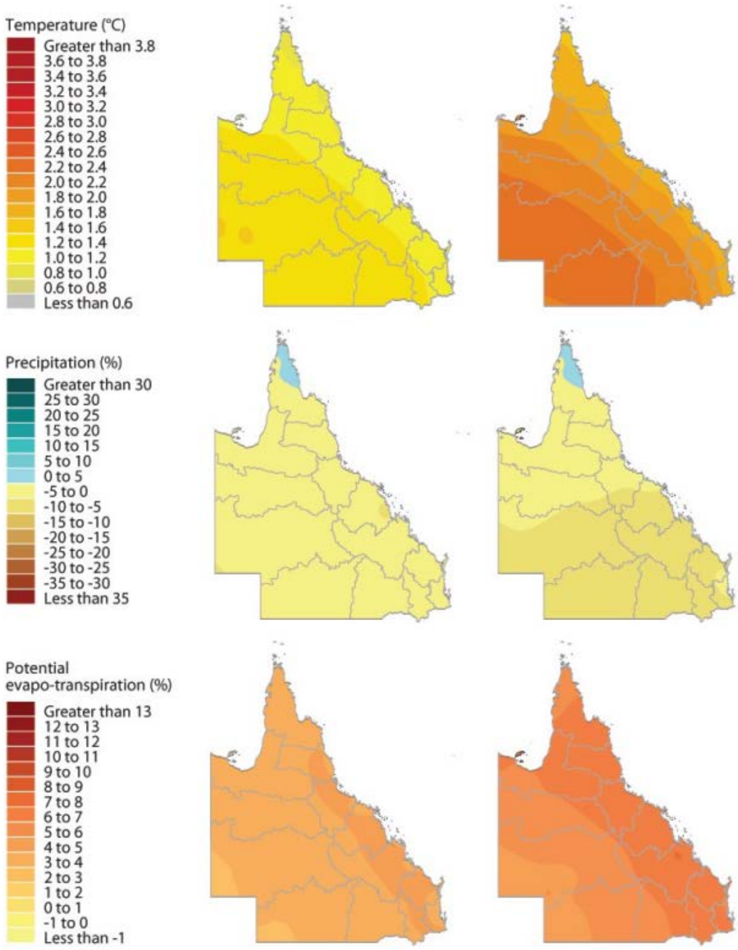


Figure 2.8. Best estimate (50th percentile) of projected change in annual temperature (°C), rainfall (%) and potential evapo-transpiration (%) by 2050 for low (left) and high (right) emissions scenarios (Source: OCC 2009, based on CSIRO data set).

2.4. Soil resource

The great diversity of soils in Australia is the result of several factors including parent material, climate, topography, organic activity and age. The predominant soil types of the cereal belt in Australia (from north-eastern to south-western Australia) include Chromosols, Kandosols, Sodosols, and Vertosols, with significant areas of Ferrosols, Kurosols, Podosols, and Dermosols (Isbell, 2002), covering approximately 20 Mha of arable cropping and 21 Mha of ley pastures (Dalal and Chan, 2001). North-eastern Australia has a subtropical cropping belt that extends from the Liverpool Plains region of New South Wales (~328S) to the Central Highlands of Queensland (~228S). Major cropping soils are black, grey and brown Vertosols, black, red or brown Sodosols, red and brown Chromosols and Ferrosols (Webb et al. 1997). Vertosols and Ferrosols are among the dominant soil types in sub-tropical regions (Syers et al., 2001) and contribute significant amounts of global cereal production (Fageria and Baligar, 2008). Ferrosols (krasnozems) in Australia are restricted to eastern regions, occurring in intermittent, relatively small areas from Tasmania to North Queensland (Isbell, 2002). In the inland Burnett area of south-eastern Queensland, there are approximately 60,000 ha of these soils, representing about 50% of the total cropping area (Bell et al., 1997).

Ferrosols are deep, acidic, heavy-textured soils formed on basalt or other basic igneous rocks (Isbell, 2002), and the red colour comes from the high level of the iron oxides (5-20%) (Moody, 1994). The strongly developed structure of Ferrosols (Sparrow et al., 1999) is given by the Fe oxides, together with smaller amounts of free aluminium oxides (Moody 1994) and relatively high organic matter content (Oades, 1995). Ferrosols can be very productive agricultural soils, when nutrient limitations are overcome with fertilisers (Sparrow et al., 1999). The value of bulk density is more likely to increase following the loss in organic matter in Chromosols, Kandosols, and Kurosols, compared with Ferrosols, where iron oxide and Al predominate. The main reason is that the organic matter of these soils (Chromosols, Kandosols, and Kurosols) is prominent in aggregate formation and stabilisation (Dalal and Bridge 1996). The soil types are broadly grouped into soil orders based on the Australian Soil Classification system **Table 2.1**.

Table 2.1. The key information about Queensland dominants soils

Soil type	Key information
Vertosols	Vertosols are the most common soil in Queensland - characteristics include: • brown, grey or black soils which crack open when dry • they commonly form hummocky relief called gilgai • very high-soil fertility—ability to supply plant nutrients • Large water-holding capacity.
Ferrosols and Dermosols	• Ferrosols are well-drained soils with red or yellow-brown colour and have clay-loam to clay textures. This soil type is usually associated with previous volcanic activity and is mainly located along the Great Dividing Range. Large areas of these soils occur around Kingaroy and Atherton where they are used for intensive crop production. • Dermosols are red, brown, yellow, grey or black and have loam to clay textures. This type of soil covers the higher-rainfall coastal and sub-coastal regions. Important areas of these soils are the Burdekin delta
Chromosols and Kurosols	Both these soil orders are texture-contrast soils. Kurosols are strongly acid (pH below 5.5) whereas Chromosols are not. Extensive areas of Chromosols are in the Western Downs and the Maranoa districts - west of the Great Dividing Range. Kurosols occur along the coast, mainly in southern Queensland.
Kandosols	Kandosols are red, yellow and grey massive earths. They generally have a sandy to loamy-surface soil, grading to porous sandy-clay subsoils with low fertility and poor water-holding capacity.
Sodosols	Sodosols are texture-contrast soils with impermeable subsoils due to the

	concentration of sodium. These soils occupy a large area of inland Queensland. Generally Sodosols have a low-nutrient status and are very vulnerable to erosion and dryland salinity when vegetation is removed.
Calcarosols	Calcarosols are lime-rich soils with sandy or loamy textures that may become more clayey with depth. They cover less than 0.5% of the state and occur in the arid western areas of Queensland; on calcium-rich sedimentary rocks, limestone and windborne deposits.
Rudosols, Tenosols and Podosols	These soils orders generally have a low fertility and low water-holding capacity. Rudosols and Tenosols are poorly developed but widespread and can be shallow and stony. The most extensive areas of these soils are inland from Cairns. Podosols occur in the more humid coastal regions including areas such as Fraser Island and Shelburne Bay. Podosols occupy less than 1% of the state.
Hydrosols and Organosols	Hydrosols are soils that are saturated with water for long periods of time - typically a grey (or greenish-grey) colour. This soil type covers less than 1% of the state and is mainly found near coastal areas. However, many inland wetlands are dominated by Hydrosols even though these areas may only be intermittently inundated. Organosols are dominated by organic materials—commonly referred to as peats. They do not exist in large areas in Queensland but occur as small pockets in the more wet areas—along the humid coastal environment.

2.5. Fertiliser use and management

This section discusses fertiliser consumption, particularly in Australia. Nitrogen and its dynamics in agricultural systems are also examined and reviewed based on the evidence available in the scientific literature. Plant growth and development require a number of nutrients, (Archer, 1988). Primary nutrients, secondary nutrients and micronutrients vary depending on the amount of each of these required by the plant (Darwich, 1998).

In Australia, about 1.1 million tonnes of nitrogen, 0.5 million tonnes of phosphorus and 0.2 million tonnes of potassium are used each year to fertilise crops (ABARE, 2008). Fertiliser consumption has increased over the last three decades (Ryan, 2010) as shown in **Figure 2.9**. The common fertilisers used in Australia are urea 47%, di-ammonium phosphate (DAP) 70%, mono-ammonium phosphate (MAP) 47%, single superphosphate (SSP) 28%, and lime 2% (FIFA, 2005). High N concentration (46% N), high solubility and low cost to manufacture, store, and transport are the main factors that have made urea a more consumable form of fertiliser in the world (Prasad et al., 1998). Phosphates and nitrogen are essential elements for cereal crops, which account for 53% of total Australian fertiliser nutrient consumption by crop and pasture (ACCC, 2008; FAO, 2013). The amount of N and P applied to cereal crops in Australia ranged from 150 to 250 kg N ha^{-1} $year^{-1}$ (Gourley and Ridley, 2005).

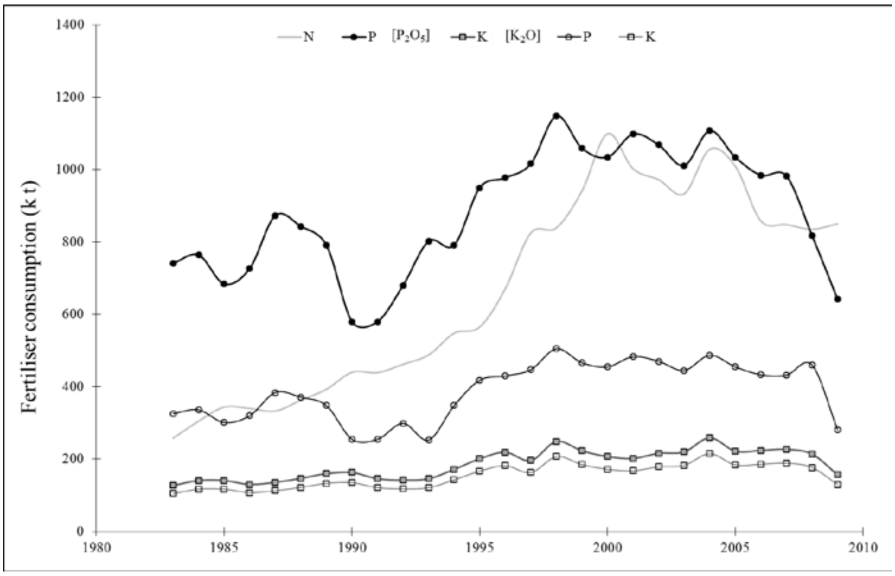


Figure 2.9. Fertiliser consumption in Australia: by product and element from 1983 to 2009 (Ryan, 2010).

In Australia, since 1975, fertiliser price has also gradually increased **(Figure 2.10)** due to rapidly increasing global fertiliser prices (ABARE, 2008; Ryan, 2010). These increases have been caused by a substantial increase in world demand for fertilisers, associated with an expansion in agricultural production and by rises in the variable costs of the agricultural production (ACCC, 2008).

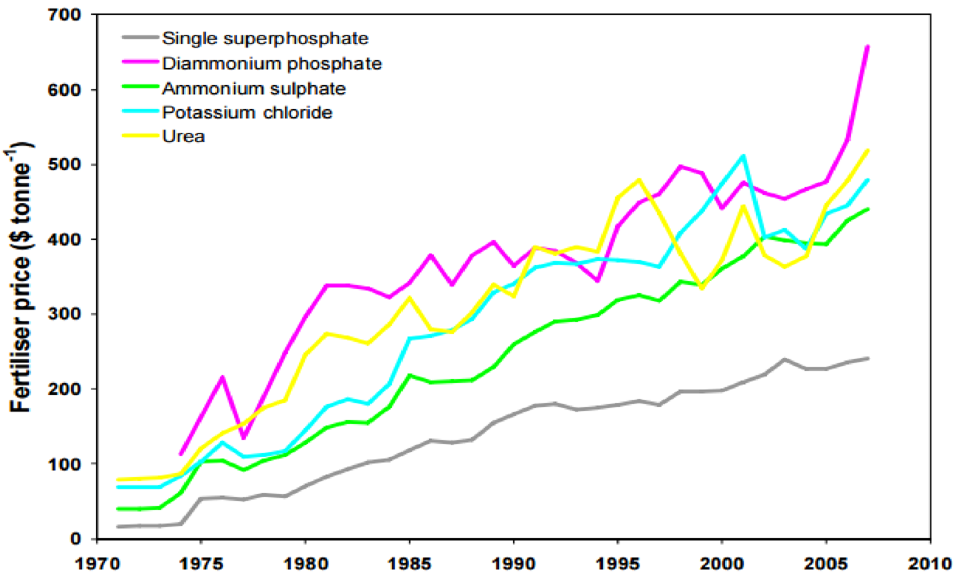


Figure 2.10. Average price of different fertilisers in Australia from 1970 to 2007 (ABARES, 2007).

2.6. Mechanisms of nutrients uptake by crops

Crop nitrogen uptake is affected by several factors indicated by Nielsen (1983), which include the concentration of nutrients in the rhizosphere and root density. The process of nutrients uptake by crops involves the use of energy which is provided by cell metabolism (Mengel and Kirkby, 1987). The nutrients can be absorbed by the plant from the soil by three mechanisms.

- Mass flow, the first mechanism, occurs when nutrients are transported in solution by means of a water flow from the soil matrix to the roots (Divito et al., 2011) and it is therefore driven by plant transpiration (Kirkby et al., 2009). Hence, the amount of a particular nutrient taken up by the plant is dependent on the volume of water entering the roots and the concentration of the nutrient in the solution (Divito et al., 2011).
- The second mechanism of nutrient uptake by the plant from soil matrix is diffusion. This mechanism occurs when plant nutrients are transported due to their relative concentrations between the soil solution in the rhizosphere and the root surface and it is induced by nutrient removal during uptake (Barber et al., 1963; Kirkby et al., 2009). Diffusion becomes significant only within short distances from the root surface, as this mechanism is affected by a gradient in the nutrient concentration and also by the volume of the water entering the roots (Divito et al., 2011).
- Root interception is the third mechanism for nutrient uptake and is due to the growth and extension of the roots through the soil profile, which makes contact with plant nutrients (Darwich, 1998). High concentration of hydrogen ions which are released by plant roots (Divito et al., 2011) would promote the exchange of cations with clay

particles in contact with plant roots. The relative importance of each mechanism largely depends on the crop and the soil type (Barber et al., 1963).

Throughout Queensland, continuous cropping has led to a decline in the fertility of many soils, especially on the Darling Downs, one of the oldest cereal growing areas in the State. Nitrogen fertiliser, which is applied to cereal crops at, or just before planting, is a major cost of production, especially for irrigated crops, where a high rate of fertiliser is often needed. Where wheat follows a summer crop very little N may become available from soil reserves because of an insufficient fallow period. Thus fertiliser N may constitute the major portion of the N supply for the wheat crop (Strong, 1981). Depending on the extent of the deficiency, insufficient nitrogen could reduce the yield or the protein content or both of the grain. Therefore, crop response to fertiliser management is an important matter to be reviewed in the following section.

2.7. Crop response to applied nutrients

Wheat and sorghum are the dominant winter and summer cereal crops, respectively in the region (Unkovich et al. 2009) and response to fertiliser N have been shown to vary depending on the soil condition and the length of the preceding fallow. Further intensification of cropping is required in attempts to further increase food production, requiring larger and more frequent inputs of fertiliser N. A proportion of this fertiliser can be lost to the environment by gaseous (denitrification and volatilisation) or water (leaching) mediated loss pathways, with production of nitrous oxide (N_2O), a potent greenhouse gas, an issue of current concern. To improve the crop utilisation of applied N, ‘enhanced efficiency fertilisers’ (EEFs) have the potential to enhance the agronomic and recovery efficiencies of fertiliser, while simultaneously reducing its environmental losses. One of the available approaches is managing soil compaction through controlling the machinery traffic in the paddock (Tullberg et al., 2018).

2.7.1. Most economic rate of nitrogen (MERN)

The relationship between increases in crop yield and additional fertiliser is known as fertiliser response curve (FAO, 1966). Yield-to-nitrogen response relationships can be curves are used to derive the optimal rate of nitrogen application (Walley et al., 2001). The increments in crop yield from each successive application of a given plant nutrient become progressively smaller; ultimately, a point in the curve is reached where an additional input of fertiliser does not result in the yield of the crop increasing significantly to outweigh the cost of the nutrient (Troeh and Thompson, 1993). In other words, the law of diminishing returns would suggest that further gains would become more difficult and less economically attractive to achieve if applying one additional unit of nitrogen fertiliser to the cereal crops (Hochman et al., 2012). The economic optimum N fertiliser rate is the N application rate where the cost of applying one additional unit of fertiliser produces the maximum return of the crop yield (Robertson et al., 2009). The optimum rate of nitrogen fertiliser depends upon the price of the grain yield and the price of N fertiliser (Ghosh et al., 2015). A nitrogen response curve for cereal crops can be described using a quadratic equation (James and Godwin, 2003; Kachanoski, 2009). The quadratic function assumes that yield is related to applied nitrogen by the following equation.

Given,

$$y = a + bx - cx^2 \qquad (\mathbf{2.1})$$

where: a, b, and c are the regression coefficients, y is the crop yield, and x is the nitrogen application rate.

Then,

$$\frac{dy}{dx} = b - 2cx' = 0 \qquad (\mathbf{2.2})$$

Therefore,

$$x' = \frac{b}{2c} \qquad (\mathbf{2.3})$$

where x' is the nitrogen application rate at the maximum of yield response curve. The most economic rate of nitrogen (MERN) is identified when the differential is equated to the price ratio P_R, which is the price of nitrogen P_N divided by the price of grain P_C:

Thus,

$$b - 2cx' = P_R \qquad (\mathbf{2.4})$$

Then,

$$R_P = \frac{P_N}{P_C} \qquad (\mathbf{2.5})$$

And,

$$MERN = \frac{(b - P_R)}{2c} \qquad (\mathbf{2.6})$$

The price ratio, P_R, is identified as the break-even ratio and it indicates the extra return of the produce that just covers the extra unit of nitrogen added. At this point, the economic return from applied nitrogen is maximised. Nitrogen rates lower than MERN lead to economic losses since crop yield is restricted by nitrogen supply, while application of higher nitrogen rates than MERN provides potential for nitrogen losses, through leaching or gaseous emissions, as above this point the efficiency at which nitrogen is converted into grain yield starts falling (Antille et al., 2017). There is also an economic loss simply because of diminishing returns. Similarly, applying more than a plant needs can affect the crop productivity by reducing farm profitability (Addiscott et al., 1991). Nitrogen-use efficiency can be determined by using the reviewed methods that explained in the next section.

2.7.2. Nitrogen use efficiency (NUE)

Nitrogen-use efficiency is a complex term with many components. In addition, a great degree of compensation takes place among the components. Nitrogen use efficiency of a crop refers to the relative balance between the amount of fertiliser taken up and then used by the crop versus the amount of fertiliser supplied (Baligar et al., 2001). To measure or quantify NUE, the term most widely used is a ratio that considers an output (biological yield or economic yield) as the numerator and input (N supply) as the denominator. The biological yield can include either total aboveground plant dry matter or total plant N, whereas the economic yield includes either grain yield or total grain N. The N supply can be from soil, fertiliser (organic or inorganic), or soil plus fertiliser (Ladha, et al., 2005). The (1) ratio of yield to N supply is commonly referred to as agronomic efficiency of N [A_E], (2) the ratio of plant N to N supply is referred to as recovery efficiency of N [NUE], and (3) the ratio of yield to plant N is referred to as physiological or internal efficiency of N [P_E] (Novoa and Loomis, 1981).

Several methods are available to determine nitrogen use efficacy (NUE). Researchers chose one or another as ‘‘practical’’ with their need, time, means, and feasibility of experimentation. Nonetheless, the following forms of A_E, NUE, and P_E efficiency ratios are most widely used because they are easy to use and inexpensive.

In field studies, fertiliser use efficiency is determined based on either differences in crop yields or nutrient uptake between fertilised plots and an unfertilised control (Roberts, 2007). Cassman et al. (1998) and Johnston and Poulton (2009) provided the definitions: this method requires that the treatments in the same experiment have and have not been applied with nitrogen fertiliser. The data can then be used in two ways, as follow:

- **Direct methods:** this method consists of the use of ^{15}N and the labelling of N-fertiliser with this isotope which allows measuring the N from the fertiliser in the growing crop, the harvested product and also the residual nitrogen remaining in the soil at harvest. The results are usually expressed in percentage. It generally acknowledged that they can provide accurate estimates of nitrogen use efficiency; however, the main disadvantage of ^{15}N experiments is the cost associated with their use.
- **Difference method:** This method requires that the treatments in the same experiment have (fertilised) and have not been applied with nitrogen fertiliser (control) (Baligar et al., 2001). The data can then be used in two ways, as follow:

- **Nitrogen use efficiency using crop yield:** this is often considered as the agronomic efficiency (A_E) of applied nitrogen fertiliser:

$$A_E(kg\ kg^{-1}) = \frac{(Y_N - Y_{N=0})}{N_{Rate}} \qquad (\mathbf{2.7})$$

where: Y_N and Y_N=0 are the crop yields (kg ha^{-1}) corresponding to the treatments (N≠0) and the control (N=0) respectively, N_{Rate} is the nitrogen application rate (kg ha^{-1}).

- **Nitrogen use efficiency using nitrogen uptake:** this is usually considered as the 'apparent recovery' (R_N) of applied nitrogen fertiliser.

$$NUE\ (\%) = \frac{(U_N - U_{N=0})}{N_{Rate}} \times 100 \qquad (\mathbf{2.8})$$

where: U_N and U_N=0 are the nitrogen uptake by crop (kg ha^{-1}) corresponding to the fertilised crop (N≠0) and the control (N=0), respectively. Nitrogen uptake is the nitrogen recovered in grain and is obtained by multiplying grain yield (kg/ha) by total grain nitrogen (%).

- **Indirect methods**

- **Partial factor productivity of applied nitrogen (I_P):** this is the ratio between the yield (kg) and the nitrogen applied to the crop.

$$I_P = \frac{Y_N}{N_{Rate}} \qquad (\mathbf{2.9})$$

- **Physiological efficiency of applied nitrogen (P_E):** this can be calculated by the formula below.

$$P_E = \frac{(Y_N - Y_{N=0})}{(U_N - U_{N=0})} \qquad (\mathbf{2.10})$$

where: all of the (Y_N, $Y_{N=0}$, U_N, $U_{N=0}$) were defined in the previous equations.

Nitrogen-use efficiency can potentially be improved by applying nutrients at the right rate, time and place and accompanied by the right agronomic practices (Ghosh et al., 2015). The use of modern farming techniques to manage soil compaction can be potentially enhanced NUE in the crops by reducing the fertiliser input (Tullberg, 2008). The effects of soil compaction and hydraulic properties, crop performance and environment are reviewed in next section.

2.8. Constraints of soil to crop production and profitability

Soil structure largely determines the nature of the physical processes that occur within a soil (Dexter, 1988; Kooistra and Tovey, 1994). A good soil structure is the one that exhibits a high degree of heterogeneity between the different components or properties of soil (Chamen, 2006). The agricultural mechanisation has short and long-term negative effects on soil structure (Alakukku, 1996). Soil strength tends to increase as soil moisture content decreases but is elevated by stress-induced increases in bulk density, penetration resistance or shear strength (Whalley et al., 2004). Soil compaction can occur naturally by wetting and drying or freezing and thawing (Larson and Allmaras, 1971), or by external causes such as using heavy machinery in the agricultural operations (Cohron, 1971; Harris, 1971). The use of heavy farm equipment alone results in approximately 68 million ha of compacted land globally (Oldeman et al., 2017). Soil compaction ranks as the major problem in terms of damage to soil resources (Flowers and Lal, 1998). The impact of compaction on soil characteristics and crop yield varies with the weather, soils and management practices (Gregorich et al., 2011). Soil compaction results in pore size reduction and more non-connected pore space, which is causing more resistance to root growth (Kulkarni, 2010).

Although there are benefits of moderately compacted soil to increase root-to-soil contact (Czyż, 2004), excessive compaction precludes the free soil profile exploration by crop roots which is the main cause of yield depression. Over-compaction can also reduce carbon mineralisation and uptake of water and nutrients by crop roots, and cause denitrification (Yamulki and Jarvis, 2002; Van Groenigen et al., 2005). Soil compaction can have both a direct and an indirect impact on crop performance; directly, compaction interferes with the crop's ability to extract water, nutrients and air; the indirect influence is associated with timeliness which means the additional time that may be taken to prepare a seedbed, and the quality of the seedbed, once prepared (Chamen, 2006). Low and high compaction 1.14 and 1.34 g cm^{-3} in a silty clay soil (clay 46%, silt 50%, sand 4%, organic matter 4.1% in the plough layer), respectively, reduce grain yield, biomass production and nutrient uptake of barley (*Hordeum vulgare* L.) compared to intermediate compaction of 1.24 g cm^{-3} (Arvidsson, 1999). Compaction of clay soil has a significant effect on yield and nitrogen uptake, where four passes reduced the yields by 4% and nitrogen uptake of annual crops by 9%, while compaction of the organic soil with four passes decreased the yield by 1% and nitrogen yield by 4% (Alakukku and Elonen, 1995). High penetration resistance reduced root growth and affected water and nutrient uptake by crops (Rusu et al., 2011). Soil with high bulk density impedes the growth, distribution and function of roots (Montagu et al., 2001; Bengough et al., 2006; Kaspar et al., 1991; Tardieu, 1994). Compaction influences soil physical properties which can negatively reflect on crop performance.

Crop growth is lower than the maximum potential when the uptake of water, oxygen or nutrients is less than the demand of the crop (Boone and Veen, 1994). The uptake of nutrients transported by diffusion is more affected by compaction than for nutrients transported by mass flow (Arvidsson, 1999). The reason for lower uptake in comparison to moderately compacted soil, 1.24 g cm^{-3}, is because of reduced root-to-soil contact (Arvidsson, 1999), which may promote nutrient uptake (Veen et al., 1992), but generally reduces root growth through its effect on aeration and mechanical resistance. The soil compaction also increases mass flow transport (Kemper et al., 1971) and the diffusion coefficient at given gravimetric water content (So and Nye, 1989; Bhadoria et al., 1991). Reduced oxygen content in soil compaction due to reduced porosity and structural degradation can affect the transport, absorption and transformation of nutrients (Lipiec and Stępniewski, 1995). In Pakistan and under a sandy clay loam soil, approximately 38% reduction in grain yield of wheat crops was reported when the subsoil compaction was carried out at 0.15 m depth to a bulk density of 1.93 g cm^{-3} (Ishaq et al., 2001). The level of grain yield increase under non-compacted soil was ranged (30-55%) based on the results reported in numerous past studies (e.g., Radford et al., 2001; Hamza and Anderson, 2003; Sadras et al., 2005). The decline in grain yield and yield components were caused by compaction which was able to reduce root mass density by up to 35% (Chan et al., 2006), and that means root exploration was also reduced due to the compaction, and thus limited extraction of soil water and nutrients and moisture (Ahmad et al., 2009). Other studies (e.g., Boone and Veen, 1994) have attributed the poor agronomic performance under compacted soil to the limited supply of water, oxygen and nutrients from the soil to the root system or a limited activity of the root system. The effect of soil compaction on soil, crop and environment can be overcome through the use of optimal tillage systems. Next section is going to explain the common tillage systems used in the Australian farms.

2.9. Tillage systems

Soil management systems can affect soil physical and hydraulic properties and thus have a direct bearing on crop performance (Hill, 1990). In general, tillage systems are sequences of operations that manipulate the soil in order to produce a crop (Boydaş and Turgut, 2007). Populations, diversity and activity of soil organisms may all be affected by the complex impact of tillage systems on the soil's physical, chemical and biological characteristics (Kladivko, 2001). This section discusses the tillage systems in Australia, with particular regard to conventional and conservation techniques.

2.9.1. Conventional Tillage

Conventional tillage is defined as a traditional technique commonly used in a given field to prepare a seedbed and produce a given crop (Reeder, 2000). This tillage system usually refers to a primary (e.g., mouldboard, row disc, deep ripper, chisel) and secondary tillage operations, harrowing operations for seedbed preparation (Schuller et al., 2007). Despite tillage operations are necessary to remove weeds and smooth the soil surface, conventional tillage practice leaves the soil bare for considerable periods before the crop cover develops and the bare soils can be subject to intense rainfall. This frequently causes soil erosion, which presents problems for the longer-term sustainability of both the soil resource and crop production (Martínez et al., 2008). Conventional tillage can also increase soil compaction by using multi-agricultural operations.

2.9.2. Conservation Tillage

Conservation agriculture (CA) is the generic name for a set of farming practices designed to enhance sustainability by reducing soil degradation (Rusu et al., 2011). A conservation tillage system includes any tillage or sowing system (e.g. zero-tillage, minimum tillage) that maintains at least 30% soil cover with crop residue after planting (ASAE, 1993). Although no-tillage has been substantially adopted in the last decade in Australia, the rate of adoption across regions are affected by economic, management and climatic factors (D'Emden, et al., 2006). Studies (e.g., Hill and Crus, 1985; Chang and Lindwall, 1989) have found no significant differences in bulk density between a conservation system with the presence of mulch and conventional tillage systems, which might be due to the sizes of machinery were lighter at that time. Soil water status is also improved under a conservation tillage system due to reduced evaporation and surface runoff (Zhai et al., 1990; Šarauskis et al., 2009).

2.9.3. Zero-tillage

No-tillage or direct drilling usually have lower traffic intensities due to reduced numbers of operations generally required by this system (e.g. pre-sowing cultivation) (Botta et al., 2006). Therefore, the energy required for crop establishment is also less compared with the conventional tillage systems (Burt et al., 1994), which has an effect on profitability. Some of the benefits of zero-tillage are: improved timing of sowing, lower fuel costs, higher crop productivity, lower soil erosion and better water quality, and greater soil moisture retention and water infiltration (Reicosky, 2015). However, Botta et al. (2008) attributed the reduction in crop yield after long-term continuous direct drilling to increased soil compaction, weed population and root diseases. These risks over several years of a continuous no-tillage system can be overcome by conducting strategic or occasional tillage operations (e.g., Dang et al., 2018).

2.9.4. Occasional strategic tillage

Farmers usually resort to an occasional strategic tillage operation to combat constraints of no-tillage farming systems (Argent et al., 2013; Kirkegaard et al., 2014). The impact of occasional strategic tillage on agronomic, soil and environment has been investigated for short and long-term (4-5 years) by a number of studies (Kettler et al., 2000; Wortmann et al., 2010; López-Garrido et al., 2011; Crawford et al., 2015; Liu et al., 2016; Rincon-Florez et al., 2016). They stated that an important consideration associated with adopting this system is the increased risk of erosion and runoff especially in the case of an intense rainfall immediately following a strategic tillage operation, which could pose a serious problem.

Farming in dry regions with highly variable climate, such as South East (SE) Australia (Nicholls et al., 1997), is inherently a highly risky enterprise (Connor, 2004) and production of high yield is uncertain. Leading grain farmers have led the way in adopting new technologies and therefore provide insights into future trends in productivity growth. Over the last 20–30 years, these grain farmers initiated and participated in the rapid development and adoption of new and improved crop management practices. They have made significant changes to production systems, leaving behind traditional farming practices in which cereal crops were sown into cultivated soil, often after a long fallow period. No-till farming, where crops are now sown every year into standing stubble left from the previous crop, is now the norm for leading farmers. Nutrient supply and timing of operations have also improved markedly (Kirkegaard et al., 2014). It is significant, therefore, that leading farmers in SE Australia are concerned that their crop yields have reached a plateau and are asking the question ‘Where are the next production gains coming from?’

Next section gives some details about the traffic techniques that commonly investigated in agriculture. This section also examines some of the reported benefits associated with adoption of CTF, and the potential implications for nitrogen use efficiency, environment and farm profitability. The obstacles against adoption of CTF are also reviewed in the next section based on the evidence available in the scientific literature.

2.10.Traffic farming systems

Efficient agricultural mechanisation is an important factor underlying high productivity (Tullberg et al., 2007). Larger machinery is often associated with timeliness, higher work rates, and lower labour requirements (Chamen et al., 1992b; Vermeulen and Chamen, 2010). One of the drawbacks is the progressive increase in machinery weight (Chamen et al., 1992b). Wheel traffic by heavy agricultural machinery can lead to compaction and degradation of soil physical properties. Traffic-induced soil compaction has negative impacts on soil properties such as bulk density, mechanical impedance, porosity and hydraulic conductivity (Hamza and Anderson, 2005), which subsequently decreased root penetration, water extraction, and plant growth (Passioura, 2002). Although there are several practice techniques for soil compaction management **(Figure 2.11)** (Soane et al., 1979; 1982), research has shown that controlled traffic farming (CTF) system has fundamental advantages in maintaining soil structural conditions with lower inputs of energy (reduced draft), improved trafficability and timeliness compared with non-CTF (Chamen and Longstaff, 1995; Tullberg, 2000; McHugh et al., 2009).

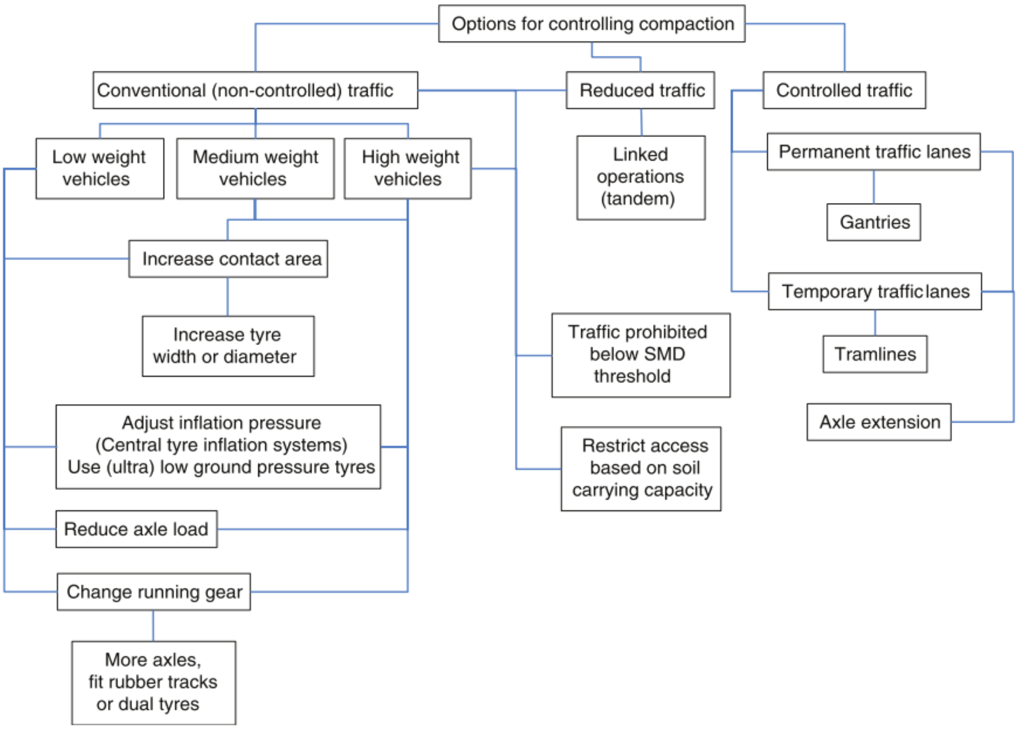


Figure 2.11. Options for controlling compaction in agricultural soil (redrawn and modified from Soane et al. 1979, 1982). SMD, Soil moisture deficit.

Controlled traffic is a cropping system in which the wheel traffic lanes and the crop zones are totally and permanently separated (Taylor, 1983). In wheel traffic lanes, tyres need strong and compacted soil for better tractive efficiency (the ratio of drawbar power to axle power); in the cropped zone, roots require a soft soil condition and low level of compaction to enable root elongation and plant growth. Controlled traffic allows optimisation of soil conditions for each of these directly opposed requirements in the same field (Taylor, 1994). Based on work compiled by Hamza and Anderson (2005) it is possible to lessen the risk of soil compaction caused by machinery traffic. Reducing pressure on soil can be achieved by: (a) decreasing axle load and/or increasing the contact area of wheels with the soil; (b) reducing the number of passes by farm machinery; (c) confining traffic to certain areas of the field (CTF system). Improved soil condition under CTF system as a result of the layout and the design of the permanent traffic lanes which are reduced to be occupied less than 15% of cultivated field area compared to more than 65% trafficked area in farms that CTF is not practised (ACTFA, http://actfa.net/). Therefore, the CTF system is regarded as a practical and cost-effective technology to minimise the impact of traffic-induced soil compaction (Tullberg, 2010; Kingwell and Fuchsbichler, 2011; Chamen et al., 2015). Despite the benefits of CTF, global adoption of this system appears to be small with the exception of Australia, where it is used by approximately 30% of grain growers (Tullberg et al., 2007; Chamen, 2015).

Recent studies (e.g., Antille et al., 2015a) have shown that CTF systems have the potential to either reduce nitrogen (N) fertiliser inputs without compromising crop yield or increase crop yield for a given fertiliser input. This is supported by studies showing enhanced structural conditions in soils established under CTF (e.g., McHugh et al., 2009) and by enhanced nutrient uptake in the absence of traffic compaction (e.g., Lipiec and Stępniewski, 1995). Improved crop response to nitrogen fertiliser application under CTF system enhanced farm profit.

The economics of change to CTF are dominated by the conversion costs, but these in turn can be reduced considerably through knowledge transfer and long-term planning. The costs of moving to a CTF system are often seen as a barrier to adoption, particularly the cost of machinery modifications which is around AUD40000 (Bowman, 2008). However, a controlled traffic system reduces farm costs in different ways. Reducing farm operations overlap is one of the main benefits of the CTF system. Accurate positioning of each operation under the CTF system has been shown to reduce the compacted area and, consequently, the farm inputs required, by the order of 15-30% (Webb et al., 2004; Robertson et al., 2007; Bowman, 2008). The estimated fuel usage for the conventional system (non-CTF) is more than double compared with the CTF system (52 l ha^{-1} and 20 l ha^{-1}) respectively (Bowman, 2008) due to the higher energy requirements of pulling implements through compacted soil. Furthermore, CTF system can also reduce the number of labourers and increase the speed of agricultural operations, consequently reducing farm costs (Bowman, 2008). The greater input use efficiency in a CTF system is particularly important where the cost of inputs (fertilisers, fuel, seed and chemicals) is rising. Higher costs in random traffic systems are reflected in additional inputs such as greater fertiliser use to counter compaction-induced losses (Chamen et al., 2015). Hence, CTF represents a profitable innovation for farming systems, offering input savings and output increases (Kingwell and Fuchsbichler, 2011). In Australia, CTF represents a profitable technological innovation for arable land use (Kingwell and Fuchsbichler 2011) and has additional agronomic and environmental benefits (Chamen 2007; Tullberg 2010; Gasso et al. 2013), including reduced potential for greenhouse gas (GHG) emissions and improved fertiliser-use efficiency (Vermeulen and Mosquera 2009; Antille et al. 2015a).

There are three main gases related to greenhouse gas emissions from agriculture: nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) (Snyder et al., 2007). The contribution of N_2O is around 8% of the global warming of all greenhouse gas emissions (Loubet et al., 2011; Ranucci et al., 2011). The potential for global warming of N_2O is approximately 296 times higher than CO_2 (Snyder, et al., 2007). Agriculture accounts for approximately 12% of total global anthropogenic emissions of GHG, which amounts to 60% and 50% of global N_2O and CH_4 emissions, respectively, which arise mostly from soil management (Smith et al., 2007).

Based upon the results reported in several studies (Ball et al., 2000, 2008; Flessa et al., 2002; Yamulki and Jarvis, 2002; Ruser et al., 2006; Bessou et al., 2010), traffic-induced soil compaction is a major problem that can potentially increase N_2O emissions. Other studies have suggested that the reduction of soil compaction in CTF system has the ability to reduce gas fluxes (Tullberg et al., 2007; Vermeulen and Mosquera, 2009; McPhee et al., 2015). Soil compaction can promote denitrification and consequently, an increase in the emission of N_2O (van Groenigen et al., 2005; Bessou et al., 2010). Based upon the work of Tullberg (2008), **Table 2.2** shows the seasonal CTF was able to reduced N_2O and methane emissions compared with the random traffic system.

Table 2.2. Effects of seasonal CTF on GHG emissions compared with random traffic under black Vertosols (Tullberg, 2008).

Traffic system	Emissions (kg ha^{-1}) in 30 days		CO_2 Equivalent (kg ha^{-1}) in 30 days		Total
	N_2O	CH_4	N_2O	CH_4	CO_2 E (kg ha^{-1})
Random traffic	+ 2.04	+ 0.022	632	+ 0.52	633
Seasonal CTF	+ 1.41	- 0.146	437	- 3.37	434

Controlled traffic is not only an engineering solution to some of the unwanted effects of soil compaction, but importantly it transforms a problem of traffic-induced soil compaction (the tramlines in CTF system) into an advantage of improved trafficability and timeliness, which has additional agronomic, economic and environmental benefit (Tullberg, 2010) **(Table 2.3**). However, several barriers have also been identified that restrict the adoption of this technique in some agricultural cases (**Table 2.4)**. In most circumstances, the establishment of CTF has contributed to increased crop yields, some exceptions being reported in years of abundant moisture, where the effects of soil compaction on plant growth are smaller (e.g. Whisler et al. 1993).

Table 2.3. Perceived benefits of CTF within grain cropping system (after: Antille et al, 2015)

Factor	Description	Reference
Timeliness and field efficiency	Improved field access for all agricultural operations, particularly planting, spraying and harvesting.	ACTFA, (http://actfa.net/); Bochtis et al. (2010).
Tractive efficiency	Reduced rolling resistance, wheel-slip, fuel consumption and tillage draft force and therefore improved energy-use efficiency.	Burt et al. (1994); Tullberg (2000).
Nitrogen use efficiency	Higher nitrogen (N) recovery in crop and crop response to applied N (both grain and biomass by up to 20%). Reduced nutrients lost by leaching or denitrification (emissions).	Alakukku and Elonen (1995); Lipiec and Stępniewski (1995); Antille et al. (2015).
Runoff and soil erosion, internal drainage	Improved soil conditions (porosity and structure), hydraulic conductivity, surface infiltration, and water-holding capacity.	Li et al. (2001, 2007); Tullberg et al. (2001); McHugh et al. (2009).
Crop yield, reduced in-field crop variability	Improved crop yield (by 15% or greater) and increased soil C sequestration through greater crop residue returned to the soil.	Radford et al. (2001); Botta et al. (2007); Tullberg et al. (2007); Neale (2011); Smith et al. (2014).
Greenhouse gas emissions	Reduced potential for GHG emissions (by 20-50%), with the enhanced absorption of methane (CH_4).	Ruser et al. (2006); Tullberg et al. (2011); Antille et al. (2015); Tullberg et al., (2018).
Profitability	Higher gross margin and economic return that results from resource-use efficiency.	Chamen (2011); Kingwell and Fuchsbichler (2011); Chamen et al. (2015).
Compatibility with no-tillage (NT) and precision agriculture technologies	Demonstrated synergism between NT (minimum tillage) and CTF. Compatibility with variable rate technology but this should be preceded by CTF. There is a requirement for good (overall) soil husbandry to ensure that the implementation of these technologies can deliver tangible benefit.	Tullberg et al. (2007); Godwin (2015); Smith et al. (2014); Antille et al. (2015).

Table 2.4. Potential barriers against CTF adoption within grain cropping system (Chamen, 2006).

Factor	Description	Reference
Equipment incompatibilities, reliance on contractors	Non-matching equipment between crops in the rotation (e.g., cutter-bars or planters widths). Potential incompatibilities between owned and contracted farm equipment (e.g., track gauge, operating widths or both). Lack of qualified labour to modify farm machinery	McPhee et al. (1995), Chamen (2006), Isbister et al. (2013)
Cost of conversion, size of the farming enterprise	Difficulties in gaining access to credit, changes in interest rates and price of commodities, and associated financial risks. Adverse effects of climate on yield, such as lack of rainfall, potentially overcome by greater cropping reliability. Loss of product warranty when equipment is made CTF-compatible. Cost of guidance systems and accuracy	Kingwell and Fuchsbichler (2011), Blacwell et al. (2013), Rataj et al. (2013)
Direction of field operations, field characteristics (topography, size, shape)	Orientation of field operations permanently restricted to parallel directions but can be overcome with changes to implement the design. Potential interference of in-field infrastructure for soil erosion control (e.g., contour banks) or surface drainage. Careful design of permanent traffic lanes' layout is required	Chamen (2006) with data from Titmarsh et al. (2003); McPhee et al. (2013)
Land tenure system	Influences the motivation to change the system	Antille et al. (2015)

The second part of this study was the modelling of crop performance, which was subsequently used to assess the likely impact of soil compaction on crop productivity. Further details about crop modelling are reviewed in the next section.

2.11.Modelling of crop performance

2.11.1. Overview

Decision-making and planning in agriculture is increasingly determined for model-based decision support tools, particularly in relation to the changing climate (Palosuo et al., 2011). Crop growth simulation models applied are mostly mechanistic, because they attempt to explain not only the relationship between parameters and simulated variables, but also the mechanism of these models (explains the relationship of influencing dependent variables) (Porter and Semenov, 2005; Challinor et al., 2009; Rauff and Bello, 2015). There are numerous models used to simulate impacts of the climate change on agriculture. The crop models can be used to evaluate the impact of alternative management strategies on crop production (Ventrella et al., 2012) and on the environment (Asseng et al., 1998a), to investigate the level of crop production (Van Ittersum et al., 2013), as well as to predict the crop yield under changing climatic conditions (Asseng et al., 2013).

Several crop models were studied through different farm conditions. Palosuo et al. (2011) studied the comparison between eight crop models (APES, CROPSYST, DAISY, DSSAT, FASSET, HERMES, STICS and WOFOST). Aquacrop, CERES-Wheat models were also investigated by Castañeda-Vera et al., (2015) to compare the models in terms of modelling approaches, process descriptions and model outputs. The Agricultural Production Systems Simulator APSIM (Keating et al., 2003) is one of the few available dynamic, system simulation models capable of dealing with water and

N dynamics under different fertility management conditions (mineral and organic amendments) (Akponikpè, et al., 2010). Further details about APSIM are provided in the next section.

2.11.2. Agricultural Production Systems Simulator (APSIM)

Work on building the APSIM framework began in the early 1990s. A key and novel design concept was a focus on cropping systems as distinct from individual crops. The dynamics of the soil and system management over crop seasons became central. A key design specification was that the simulator needed to be capable of robustly representing farm management specifications that went well beyond the current imagination, so a truly generic manager design was needed (Holzworth et al., 2014a). **Figure 2.12** shows how initially APSIM inherited much of the science and knowledge built into AUSIM and PERFECT and how both of these precursors had incorporated developments from other groups (Holzworth et al., 2014a). APSIM considers as a tool which can be used to simulate different production systems (McCown et al., 1996). This software is a modular modelling framework that has been developed by the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003). The model can simulate above and belowground growth, grain yield, water and N uptake, and soil water and soil N in wheat crops (Asseng et al., 1998).

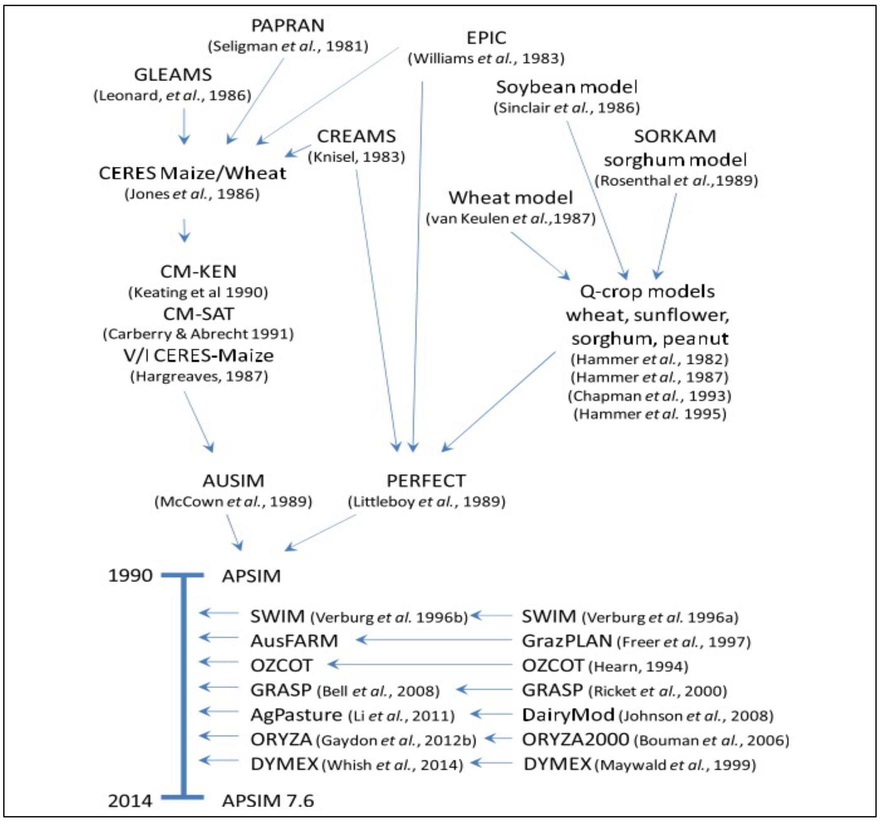


Figure 2.12. The model pedigree of APSIM, the models that have influenced APSIM inception and the external models that have been incorporated into APSIM post-1990 (Holzworth et al., 2014).

A model is defined as a unit of computation and in APSIM this represents a collection of processes. For example, a crop or water balance is considered a model whereas photosynthesis or runoff is considered a process. These process-based models interact with each other on a daily timestep (Holzworth et al., 2014a). SOILN is the module that simulates the mineralisation of N and thus the N supply available to a crop from the soil and residue roots from previous crops (Keating et al., 2003). The APSIM model consists of a number of modules (e.g., crop or water balance) and processes (e.g., photosynthesis or runoff). Based on the review compiled by Holzworth et al. (2014). **Table 2.5** provides a list of the biophysical models available in APSIM and specifies the key reference(s) for each. They are categorised into plant, soil, animal and climate models. The plant models as summarised by Holzworth et al. (2014)

simulate the key physiological processes, including phenology, organ (leaf, stem, root, and grain) development, water and nutrient uptake, carbon assimilation, biomass and nitrogen partitioning between organs, and responses to abiotic stresses. Soil models simulate the relevant processes occurring on and in the soil profile, which are including, water infiltration and movement, evaporation, runoff, and degradation, temperature variation, the cycling of nitrate, ammonium and other solutes, and soil organic matter decomposition.

In a study conducted by Hochman, et al., (2009), four methods have used to estimate water use efficiency. The first was the growing-season rainfall (GSR) method that was first proposed by French and Schultz (1984a) who observed that it could be used as an estimate of water use. Second was the in-crop rainfall method in which accumulate all daily rainfall values recorded between sowing and crop maturity. The third method was to add plant-available soil water (PAW) at sowing to the in-crop rainfall to derive an estimate of the amount of water available to a crop. In the fourth method we subtracted PAW at swing and crop maturity from the results of the third method and from APSIM to derive a crop evapotranspiration value (assuming negligible in-crop losses to runoff and drainage beyond crop root zone).

Hochman, et al., (2009) defines water use efficiency (WUE) as the ratio of grain yield (kg ha^{-1}) to crop water use by evapotranspiration (mm). A range of WUE values have emerged from the various times, locations, and methods of different studies. In South Australia, French and Schultz (1984a) determined a mean value of 6.9 kg grain/ha.mm. Angus and van Herwaarden (2001) estimated 3.8 kg grain/ha.mm or 36% of simulated potential for mean district yields from the Wagga Wagga local government area in New South Wales. Sadras and Angus (2006) determined a mean WUE value of 8.3 kg grain/ha.mm from farms and 10.1 kg grain/ha.mm from experimental plots in the

Mallee in South Australia. Yields at The Wagga Wagga Agricultural Research Institute achieved an average WUE of 15 kg grain/ha.mm with an x-intercept of 67mm (Cornish and Murray 1989). A similar WUE value (15.8 kg grain/ha.mm) was observed for modern wheat varieties from research plots at Merredin in Western Australia (Siddique et al. 1990).The existing knowledge from the scientific literature review about crop response to soil compaction and the effect of such compaction on fertiliser-use efficiency, were concluded in the next section, and utilised as a starting point in this project.

Table 2.5. The plant, soil, animal and climate APSIM models are listed with key references describing the development and testing of each model (Holzworth et al., 2014).

APSIM model	Origin/references	APSIM model	Origin/references	APSIM model	Origin/references	APSIM model	Origin/references
Plants		Lucerne	(Dolling et al., 2005)	Sorghum	(Hammer et al., 2010)	Solute	(Paydar et al., 2005)
AgPasture	(Li et al., 2011)		(Probert et al., 1998b)		(Whish et al., 2005)		(Poulton et al., 2005)
Bambatsi			(Verburg et al., 2007)	Soybean	(Robertson and Carberry, 1998)	Surface	(Connolly et al., 2001)
Barley	(Ebrahimi et al., 2016)	Lupin	(Farr'e et al., 2004)	Stylo	(Carberry et al., 1996b)	Surface OM	(Probert et al., 1998a)
Broccoli	(Huth et al., 2009)	Maize	**Origin: AUSIM-maize**	Sugarcane	(Keating et al., 1999)		
Butterfly pea			(Carberry and Abrecht, 1991)	Sunflower	(Chapman et al., 1993)	SWIM	(Huth et al., 2012)
Canola	(Robertson et al., 1999)	Millet	(van Oosterom et al., 2001)	Sweet corn	(Henderson et al., 2011)		(Connolly et al., 2002)
Centro		Mucuna	(Robertson et al., 2005)	Sweet Sorghum			(Verberg et al., 1996a,b)
Chickpea	(Robertson et al., 2002)	Mungbean	(Robertson et al., 2002)	Vine		Temperature	(Campbell, 1985)
Cotton	**OZCOT:**	Navybean	(Robertson et al., 2002)	Weed		Water (SoilWat)	(Probert et al., 1998a)
	(Hearn, 1994)	Oats	(Peake et al., 2008)	Wheat	(Brown et al., 2014)		(Verberg and Bond, 2003)
Cowpea	(Adiku et al., 1993)	Oil Mallee			Wheat (Wang et al., 2003)	Water Supply	(Gaydon and Lisson, 2005)
		Oil Palm	(Huth et al., 2014)		NWheat (Keating et al., 2001)	***Animal***	
Fababean	(Turpin et al., 2003)	Pasture	(Moore et al., 1997)		I_Wheat (Meinke et al., 1998)	DDRules	
Field pea	(Chen et al., 2008)	Peanut	(Hammer et al., 1995)		Nwheats (Asseng et al., 1998)	Graz	(Owens et al., 2009)
	(Robertson et al., 2002)		(Robertson et al., 2001b)	***Soil***		Stock	(Freer et al., 1997)
French bean	(Henderson et al., 2011)	Pigeonpea	(Robertson et al., 2001a)	DCD	(Cichota et al., 2010)	Supplement	
GRASP	(Bell et al., 2008)	Potato	(Brown et al., 2011)	Erosion	(Littleboy et al., 1992)	***Climate***	
	(Rickert et al., 2000)			Nitrogen (SoilN)	(Probert et al., 1998a)	Canopy	(Carberry et al., 1996a)
Growth	**Eucalyptus species**	Rice	**ORYZA:**	Phosphorus	(Delve et al., 2009)	E0	(Meinke et al., 2002)
	(Huth et al., 2002)		(Bouman and van Laar, 2006)	Pond	(Gaydon et al., 2012b)	MicroClimate	(Snow and Huth, 2004)
Lablab	(Hill et al., 2006)		(Gaydon et al., 2012a)				

2.12. Conclusions

This chapter has reviewed a broad outline of the factors relating to the soil compaction induced by traffic systems on crop production. This chapter has also reviewed the need for the grain industry to solve compaction problem through using an alternative approach which appears to be both environmentally acceptable and economically advantageous. The study of fertiliser use and management, climate, and soil resources and their interaction provides a better understanding of their impacts on agricultural systems in order to find a better solution to increase input-use efficiency. A brief overview of modelling of crop performance was also provided in this literature review.

From the literature review, it has been found that several studies have investigated the relationship between soil compaction and crop yield (Barber, 1997; Bouwman et al., 2002; Barłog and Grzebisz, 2004; Bolson and Kaleita, 2007; Bowman, 2008; Botta et al., 2010; Boyer et al., 2010). However, there appears to be a lack of information regarding yield response to traffic compaction and fertiliser N formulation and application rates. Most of the studies have focused on the effects of soil compaction on the crop yield, nutrient uptake and GHG emissions, within different agricultural conditions (different soil, weather, agricultural operations) compared with the south-east Queensland (study area). In traffic farming systems, there appears to be a paucity of information concerning the effects of traffic compaction on nitrogen-use efficiency and the actual yield-to-fertiliser response relationship from which optimum economic application rate of different N fertiliser formulations. In particular, there appears to be a ‘knowledge gap’ in determining this information for the case of CTF systems for subtropical edapho-climatic conditions.

Agricultural Production Systems Simulator (APSIM) is a modular modelling framework that can be utilised in this work due to the availability of its database (soil, climate, crop). In addition, it contains a suite of modules, which enable the simulation of farming systems that cover a range of plant, soil, climate and management interactions. This simulation system is well tested and validated under the Australian conditions, which is another reason for using this particular simulation system in this study.

3. FIELD STUDIES

3.1 Introduction

Field experiments have long been used in agricultural, ecological and environmental research (Lawes and Gilbert, 1880; Johnston, 1975; Johnston and Wedderburn, 1975; Campbell, 1987; Johnston, 1987; Johnston and Powlson, 1994; Leigh, 1994; Johnston, 1997). Johnston (1997) acknowledged that the value of well-designed and executed field experiments increases with time despite that the length of the experiments makes them inevitably more costly. The cost-effectiveness of long-term experiments may be increased when numerous objectives are pursued and also when experiments are conducted on well-typified sites which make it possible to extrapolate the results to wider situations (Johnston, 1997).

The field studies reported aimed to provide valuable information to farmers and stakeholders concerning the use of controlled traffic and based on sound scientific facts. Extrapolation of the data coming from this work may be possible by bringing together the experimental and modelling works used in this research as described earlier in **Chapter 1**. The experimental work conducted as part of this project combined with long-term simulation provided robust scientific evidence to allow realistic agronomic and economic assessments of the effects of CTF on soil properties, crop performance and fertiliser and rainfall use efficiency. It is therefore important to investigate the effects of soil compaction on FUE by testing a range of different fertiliser formulations, and to identify which of these formulations is more suited (or preferred) to the traffic of farming system.

This chapter focuses on the crop responses to applied fertilisers under different traffic systems, and the changes occurred in the nitrogen-use efficiency as a result of simulating a soil condition of CTF system. The experimental field work was a key component of this research and contributed to the understanding of nutrients management and dynamics in relation to soil compaction in crop production. The findings coming from the field studies will lead to the development of practical recommendations concerning fertiliser management in winter wheat and sorghum under CTF and non-CTF traffic systems. The dataset derived from these experiments was used to determine the economic benefits associated with their use in agricultural production which will be addressed later.

The objectives of this chapter are to:

1. Determine the effect of traffic compaction on the yield-to-nitrogen response relationship of winter wheat (*Triticum aestivum L.* Sunmate) and sorghum (*Sorghum bicolor* L. Pioneer G22) crops for a range of nitrogen fertiliser formulations,
2. Determine the effect of such compaction on fertiliser N use efficiency and to be able to quantify differences between for controlled and non-controlled traffic farming systems,
3. Collect soil and crop data to enable guide parameterisation and application of the Agricultural Production Systems Simulator (APSIM) to predict the long-term impact of soil compaction on crop performance (further explanation in **Chapter 4**).

3.2 Materials and methods

3.2.1. Site description

The experiments were conducted at the University of Southern Queensland (27°36'35.27"S, 151°55'50.62"E) located in Toowoomba (Queensland, Australia) during the 2015 winter season and 2015-2016 summer season, respectively (**Figure 3.1a**). Rainfall and temperature records for the experimental site are shown in **Figure 3.1 b**. Total rainfall in May 2015 (138 mm) largely exceeded average long-term (1970-2000) records for this month (57 mm), and it was relatively lower in June-July and October 2015, respectively. Overall, mean air temperatures did not depart significantly from long-term records, despite that minimum temperatures were slightly below average, particularly in early spring (2015).

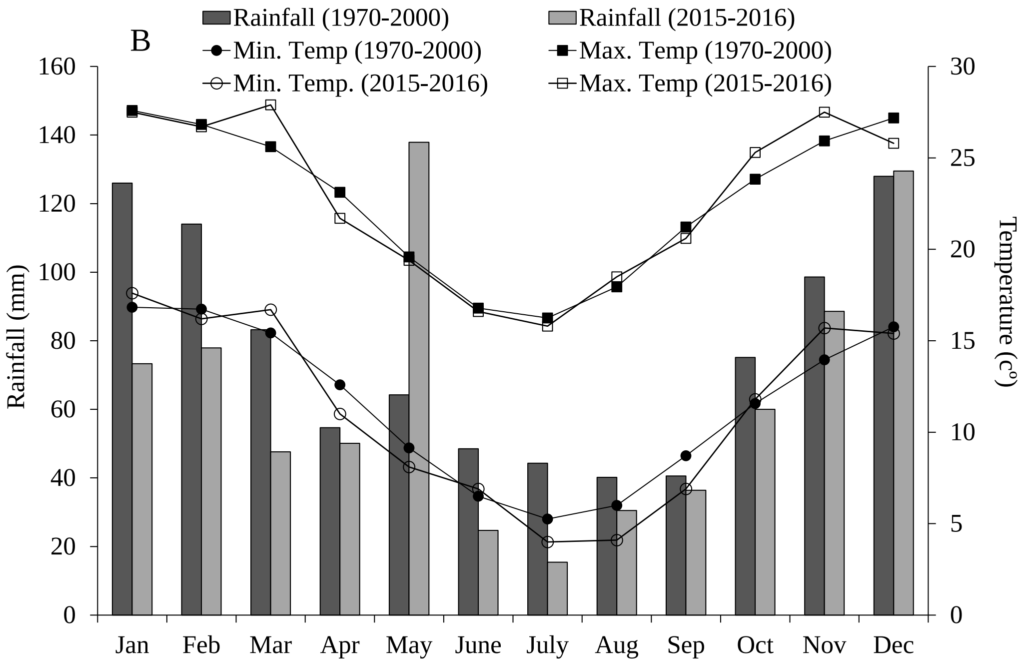


Figure 3.1. (A) Google Earth image of the location where the field experiments were conducted, (B) Monthly rainfall (mm), maximum and minimum temperatures for 2015 and long-term (1970-2000), records for Toowoomba, QLD, Australia (BOM, 2017).

The soil at the site is described in Thompson and Beckmann (1959) as a Red Ferrosol, which is well-drained and has a gentle slope (<0.8%), and it is similar to those frequently occurring in Queensland. Soil textural analyses (Gee and Bauder, 1986) for the bulked 0-200 mm layer were: 69% clay, 11% silt, and 20% sand (Clay soil). Subsoil texture has been provided, "for the 200 to 500 mm depth interval, the soil was also clay and with similar composition to the top layers, which had 68% clay, 6% silt, and 26% sand". The experimental site has been used for around 20 years for research purposes.

3.2.2. Traffic compaction and crop management

Soil compaction at the experimental sites was pre-assessed based on the earlier study conducted by Ali (2014), who measured the soil physical and hydraulic properties.

There was a requirement to remove historical compaction (300 mm depth) at the experimental site to enable the two traffic treatments (CTF and non-CTF, respectively) to be imposed (Godwin, 2011). For this, the soil was first chisel-plowed to a depth of 300 mm and this arranged based on an earlier study in SE Queensland (Antille et al., 2016), which showed that removal of compaction to such depth was sufficient to return mine-rehabilitated land affected by compaction to satisfactory crop production and that rainfall-use efficiency achieved after cultivation was ≥85% in most years. Subsequently, a power rotary harrow was used to smooth and level off the soil surface. No further tillage operations were conducted in soil representing the CTF system. The ‘random’, non-controlled traffic system (non-CTF) was established by imposing traffic compaction to the corresponding plots after conducting the tillage operations described above. This was performed by adjacent wheel-beside-wheel passes with a Belarus 920 tractor (100 HP, gross mass: 4 Mg) driven at a speed of 5 km h^{-1}, fitted with 11.2-20 (front) and 18.4 R 30 (rear) tyres inflated to the recommended pressures 0.20 and 0.10 MPa, respectively (**Figure 3.2**). The tyres were manufactured by BELARUS (made in former USSR), the tyre pressures were selected based on the manufacturer’s recommended inflation pressures. The relative difference in soil compaction between the two traffic conditions (CTF and non-CTF) was considered to be appropriate based on studies (Radford et al., 2001; Godwin, 2011; Antille et al., 2013) albeit on different soils. A total of nine passes implies overlap with the tractor were required to achieve ≈30% higher soil bulk density in the non-CTF compared with the CTF treatment. The reason for applying compaction after tillage (in non-CTF plots) was to create a known and uniform level of compaction across the experimental field as the historic compaction was variable both at depth and at the field-scale. One way to overcome this problem and minimise the uncertainty in the effects of other factors and their interaction (e.g., N rate/N formulation × compaction) was by applying tillage and imposing a known level of compaction by adjacent wheel-beside-wheel passes to simulate the non-CTF condition in both field experiments. A similar approach was also adopted by Smith et al. (2013) and Alesso et al. (2016) prior to establishing long-term experiments investigating tillage/traffic effects on crop and soil. Mean (Std.) soil moisture at the time of traffic was 18% ± 1 and 20.5% ± 0.6 (w w^{-1}) at the 0-200 mm and 200-400 mm depth intervals, respectively.

Figure 3.2. Overview of winter wheat experiment: (A) non-CTF preparation (creating a compaction); (B) deep ripper (for removing a compaction to simulate CTF soil condition); (C) wheat sowing; (D) wheat crop for CTF (right) and non-CTF (left); (E) sorghum swing; (F) sorghum crop and the division between CTF (right) and non-CTF (left).

The first field experiment was conducted to wheat (*Triticum aestivum* L. *c.v.* Sunmate⑩) which was sown on 13 June 2015 at a field-equivalent seeding rate of 60 kg ha^{-1} (Angus and Fischer, 1991), and subject to standard agronomic practice; except for the fertiliser application, which was dependent on treatment. Sowing was conducted with a 7-row conventional driller fitted with Janke press wheels and knife points at 250 mm row spacing. Phenological stages (Zadoks et al., 1974) were recorded during the crop cycle. Supplementary irrigation (solid set irrigation system) (≈20 mm) was applied after sowing to ensure crop establishment was satisfactory, and within the recommended timeframe for winter cereal crops in SE Queensland. A blanket fertiliser application (40 kg ha^{-1}) of Granulock® Starter Z fertiliser (11% N, 21.8% P, 4% SO_3, and 1% Zn) was applied to all plots at sowing based on fertiliser recommendations given in Price (2006).

The second field trial was conducted in 11th of November 2015 to test the agronomic response of sorghum (*Sorghum bicolor* L. Pioneer G22) at a field-equivalent seeding rate of 2.5 kg ha^{-1}, and subject to standard agronomic practice; except for the fertiliser application, which was dependent on treatment. Sowing was conducted with a 4-row conventional seeder fitted with knife points at 750 mm row spacing.

Sorghum crop was planted in a different plot from the plot used for wheat. There was no previous crop in none of the plots used for these experiments, and fertiliser N had not been applied to the sites in the past (at least 10 years). Therefore differences in residual nitrogen supply from the previous crop was not considered as a variable.

3.2.3. Experimental design and constraints

The experimental sites for both field studies were 100 × 25 m. The experiments were conducted in two adjacent blocks; namely: CTF and non-CTF, in which 60 plots (dimensions: 3.25-m × 5-m for wheat and 4-m × 4-m for sorghum) with 13 and 4 plant rows per plot in wheat and sorghum, respectively were laid-out in a completely randomised design, and subject to the fertiliser treatments described here. Three types of fertiliser were used: urea (46% N), urea treated with 3,4-dimethyl pyrazole phosphate (DMPP), commercially known as ENTEC® urea (46% N), and urea ammonium nitrate referred to as UAN (30% N, solution). All fertiliser treatments, including controls, were set up in triplicate (n=3). The fertilisers were hand-applied in a single band (≈50 mm) next to the plant row and incorporated at N rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1} (**Figure 3.3**). Based on the research conducted by Dalgliesh and Foale (1998), the farmer practice for nitrogen application rates in the region were between 40 and 100 kg ha^{-1} for dryland and irrigated cereal crops yield, respectively. However, to reduce the yield gap to approximately 630 kg ha^{-1}, the N application rates in Australia have to be increased to 150 kg ha^{-1}as reported by Hochman et al. (2012). Therefore, the nitrogen application rates investigated in this study were based on the work conducted earlier by Hochman et al. (2012), and James and Godwin (2003) who investigated four N application rates (50, 100, 150, 200). Their research concluded that it is possible that the true maximum yield could have been obtained at an application rate higher than those applied in the experiments as the N response curve did not show a maximum (peak) within the range of the applied nitrogen.

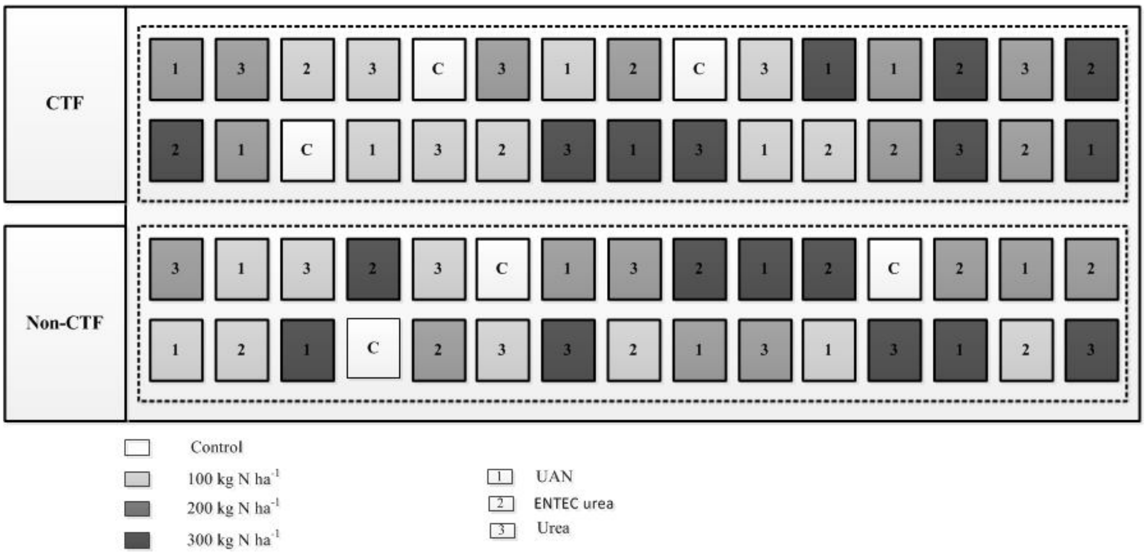


Figure 3.3. Experimental design. Where (C) refers to control, and (1), (2), and (3) are referred to as urea ammonium nitrate (UAN), ENTEC and urea, respectively.

For all fertiliser treatments, the full N application rate was halved and the splits applied at tillering (7 August 2015) and subsequently at early stem elongation (20 August 2015), respectively for the wheat experiment. In sorghum, the application of N fertiliser was banded into two halves for the rates of 200 and 300 kg ha^{-1} N: first half was applied on 30 November and the second one was applied about two weeks later on 11th of December 2015. The approach employed in my study is a side-by-side pair comparison, which is often used in research conducted in commercial farmland in situations where there are experimental constraints, such as availability of land. The plots (treatments) were replicated and had a robust experimental setup that allowed the statistical analyses to be conducted. This approach was also used by Tullberg et al. (2018) who investigated greenhouse gas emissions from a side-by-side comparison of CTF vs. non-CTF in commercial farms. The experiment undertaken in the study was laid-out in a completely randomized design with three replicated plots (n = 3). The interest of this study was to gain an understanding of the interaction between compaction and nitrogen use efficiency as affected by fertiliser rate and nitrogen formulation. Hence, replications were made for N treatments established in compacted and non-compacted soil representative of the soil conditions of non-CTF and CTF, respectively. This arrangement allowed the experiment to be conducted within the available experimental land at the university as well as to meet the project objectives.

Soil and crop measurements were determined based on the standard methods and equations. More details were provided in the next section about these measurements.

3.2.4. Soil and crop measurements and analyses

The soil physical and hydraulic properties were determined in order to guide parameterisation and application of the APSIM simulation system to predict the long-term impact of the simulated soil conditions of CTF and non-CTF on crop performance, runoff, water-use efficiency and subsequently nitrogen-use efficiency.

Soil bulk density (ρ_b) was determined for the 0-300 mm depth layer at regular increments of 100 mm by taking soil cores of 50 mm in diameter. Measurements were taken three times (n=3) before and after the traffic treatments were imposed, and ρ_b was determined based on Blake and Hartge (1986) (**Eq. 3.1)**. Maximum bulk density derived from the Proctor (BSI, 1975) test was 1.70 g cm^{-3} at a soil moisture content of 21.2% (w w^{-1}). The total porosity of soil was derived from density properties based on (**Eq. 3.2)** using a nominal particle density of 2.65 g cm^{-3}, which was considered to be appropriate for the range of soil types investigated (Hurlbut and Klein, 1977; McKenzie et al., 2002). Soil penetration resistance was measured by pushing a cone (125 mm^2 base area, 30° apex angle) into the soil to a depth of 500 mm at constant speed (0.05 m s^{-1}), and by digitally recording the force at 25 mm depth increments based on ASABE Standard EP542 (ASABE, 2013). Gravimetric soil moisture content was simultaneously determined because of its influence on soil strength (Ayers and

Perumpral, 1982). Measurements of soil moisture content and soil penetration resistance were conducted ten times (n=10).

$$\rho_b = M_d \times V_b^{-1} \qquad \textbf{(3.1)}$$

$$\eta = 1 - \frac{\rho_b}{\rho_p} \qquad \textbf{(3.2)}$$

where: ρ_b is Bulk density (g cm^{-3}), M_d is Dry soil mass (g), V_b is Sample volume (cm^{-3}), η is Total porosity (%) and $\rho_{p:}$ is particle density (2.65 g cm^{-3}).

Soil water infiltration was measured using the double-ring infiltrometer method (Parr and Bertrand, 1960). Infiltration rates were subsequently obtained by differentiating Kostiakov's equation (**Eq. 3.3**) with respect to time to describe the relationship between the rate of infiltration and time (**Eq. 3.4**). Measurements were replicated three times (n=3).

$$F_t = a \times t^n \qquad \textbf{(3.3)}$$

$$I_t = a \times n \times t^{n-1} \qquad \textbf{(3.4)}$$

where: F_t is Cumulative infiltration (mm) at time *t* (h), *a* and *n* are Constants, I_t is Instantaneous infiltration rate (mm h^{-1}) at time *t* (h).

Saturated hydraulic conductivity (K_{SAT}) of soil was also measured for both CTF and non-CTF plots using the constant head test (Klute, 1965). The outflow leachate was collected in beakers at the bottom of the column. The measurements of the leachate and timing of the duration required to obtain leachate enabled K_{SAT} to be determined (**Section 4.3.1**). Soil particle size analysis data obtained based on the Pipet method (Gee and Bauder, 1986) and the data was also used to parameterise the model simulation system in **Chapter 4**. Soil $pH_{1:5}$ (soil/water suspension) and electrical conductivity $EC_{1:5}$ (soil/water extract) were 6.22 and 0.07 dS m^{-1}, respectively (Rayment and Lyons, 2011).

The crop was harvested in the first trial (wheat) by hand-cutting the entire plant from two-linear meters of the two central rows of each plot at approximately 20 mm above the soil surface on 11 November 2015. These samples were used to determine grain yield, expressed as kg ha^{-1} at 14% (w w^{-1}) moisture content, and the following yield components: harvest index (HI), the ratio grain weight-total aboveground biomass (at harvest) (Donald and Humblin, 1976); thousand grain weight (TGW) (MAFF, 1986, Method No.: 73), number of grains per ear, and ears per square meter (ears m^{-2}). The cumulative dry matter was also determined at major phenological stages (Zadoks et al., 1974) from one-linear meter samples per plot collected from the second crop row from the edge of the plot. Similar harvesting approach was used in sorghum by hand-cutting the entire plants from the entire plot at approximately 20 mm above the soil surface on 4^{th} of March 2016. Harvested samples in sorghum were also used to determine grain yield, harvest index (HI); thousand grain weight (TGW).

For sorghum, the aboveground biomass was measured only at the time of harvesting. For wheat, the biomass was measured 8 times at the following plant stages: (tillering, stem elongation, flag leaf, booting, heading, early flowering, early grain filling, and pre-harvest). The reason is that the plant population in sorghum would have been significantly affected by removing plants whereas not so in wheat (crop configuration).

For both crops, total N in grain (MAFF, 1986, Method No.: 48) was used to estimate apparent N recovery in grain by the difference method, from which N use efficiency (NUE) was estimated. Nitrogen recovery in grain (U_F) was determined based on **Eq. 3.7**. Differences in yield between fertilised and non-fertilised crops, relative to N applied as fertiliser, were used to denote agronomic efficiency (AE), which was determined for the two crops. These relationships are shown in **Eq. [3.6] [3.7] and [3.8]**, respectively (after Baligar et al., 2001):

$$NUE\ (\%) = \frac{(U_F - U_{F=0})}{N_{Rate}} \quad (3.6)$$

$$U_F(kg\ ha^{-1}) = Grain\ yield\ \times N\%\ in\ grain \quad (3.7)$$

$$AE\ (\text{kg}\ kg^{-1}) = \frac{(Y_F - Y_{F=0})}{N_{Rate}} \quad (3.8)$$

where: NUE: Nitrogen use efficiency (%) based on apparent N recovery in grain, U_F and $U_{F=0}$: Nitrogen recoveries in grain (kg ha^{-1} N) from fertilised and non-fertilised (control) crops, respectively, N_{RATE}: Nitrogen application rate (kg ha^{-1}), AE: Agronomic efficiency (kg kg^{-1}), Y_F and $Y_{F=0}$: Grain yields (kg ha^{-1}) corresponding to fertilised and non-fertilised (control) crops, respectively.

3.2.5. Statistical analyses

The Statistical Package for the Social Sciences (SPSS-version 23) software was used to analyse the experimental data (Swan and Sandilands 1995), and involved the analysis of variance (ANOVA). Means of cone index were compared for significance using the least significant differences (LSD) at 5% level of probability, and using Duncan for the other crop and soil data at the same level of probability. Statistical analyses were graphically assessed by means of residual plots and normalisation of data was not required. Yield-to-nitrogen responses were investigated by means of nonlinear (quadratic) regression analyses. Linear and Nonlinear regression analyses were used to describe the relationships between nitrogen-use-efficiency and N application rates, from which nitrogen-use-efficiency and agronomic efficiency corresponding to the most economic rate of nitrogen were derived (data are presented in **Chapter 5**). Analytical values are reported as the mean ± standard deviation (Std.).

3.3 Results

3.3.1 Wheat

i. Soil physical and hydraulic properties

Soil penetration resistance determined for traffic treatments representing CTF and non-CTF systems is shown in **Figure 3.4**. Overall, there were significant differences ($P<0.05$) in soil cone index between the two traffic systems, particularly in the 50 to 300 mm depth interval, where penetration resistance was up to 40% higher in non-CTF. Mean values of cone index in the 0-500 mm depth range were 2.56 and 4.32 MPa (LSD 5% level: 1.32) for the CTF and non-CTF systems, respectively. No differences in penetration resistance were observed below 350 mm deep, which therefore reflects historical soil compaction not removed by tillage conducted prior to the experiment. Differences in cone index found between wheeled and non-wheeled soil were consistent with differences in bulk density between the two traffic treatments in the 0-150 mm depth interval (1.35 and 1.15 g cm^{-3}, respectively) (**Table 3.1**). Differences in soil moisture content between the two traffic systems were small ($P>0.05$).

Table 3.1. Soil bulk density reported in the two traffic treatments. The standard deviation (Std.) is shown as ± the mean value (n = 3). K_{SAT}: hydraulic conductivity.

Traffic system	Depth	Bulk density	Total porosity	K_{SAT}
	(mm)	(g cm^{-3})	(%)	(mm day^{-1})
CTF	0-150	1.15±0.04	57±0.01	1000±6.65
	150-300	1.17±0.02	56±0.02	500
non-CTF	0-150	1.35±0.04	49±0.01	50±0.08
	150-300	1.27±0.03	52±0.01	25

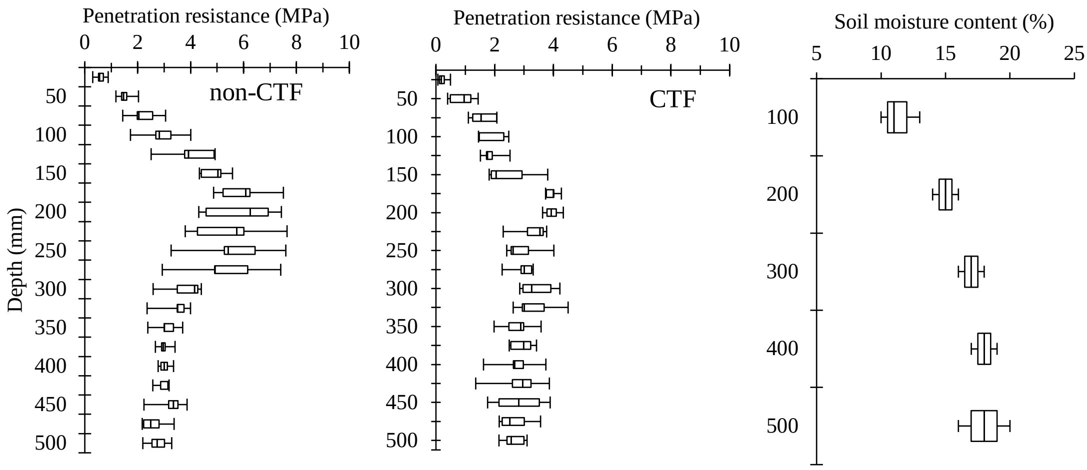


Figure 3.4. Soil penetration resistance and soil moisture content observed at the experimental sites for the CTF and non-CTF systems. For penetration resistance use P<0.05 for cone index, and P>0.05 for soil moisture content. Box plots show Min, Q1, Med, Q3, and Max, respectively. Use *n* = 10 for cone index and moisture content.

Soil water infiltration rates for the CTF and non-CTF are shown in **Figure 3.5**. Infiltration rates were significantly lower in non-CTF compared with CTF at any given time (P-values <0.05). Infiltration rates in CTF were approximately double those of the non-CTF system at any given time (mean values of 3.0 and 1.50 mm min.$^{-1}$ for CTF and non-CTF), respectively. These results are consistent with measurements of saturated hydraulic conductivity (K_{SAT}) reported earlier **(Table 3.1)**, which were 20 times higher (P < 0.05) in CTF compared with non-CTF (e.g., 1000 mm day^{-1} vs. 50 mm day^{-1}, respectively).

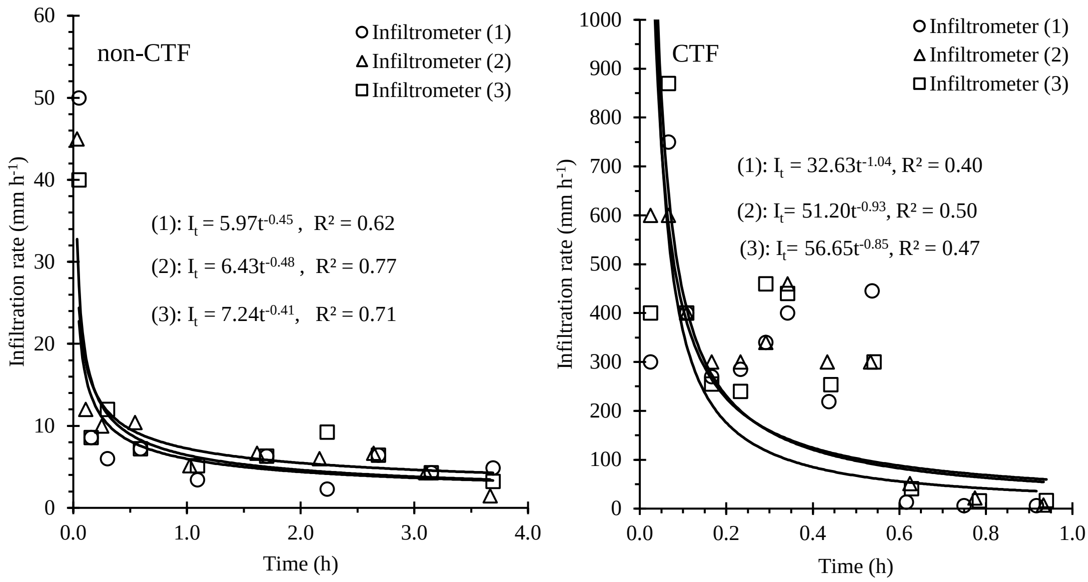
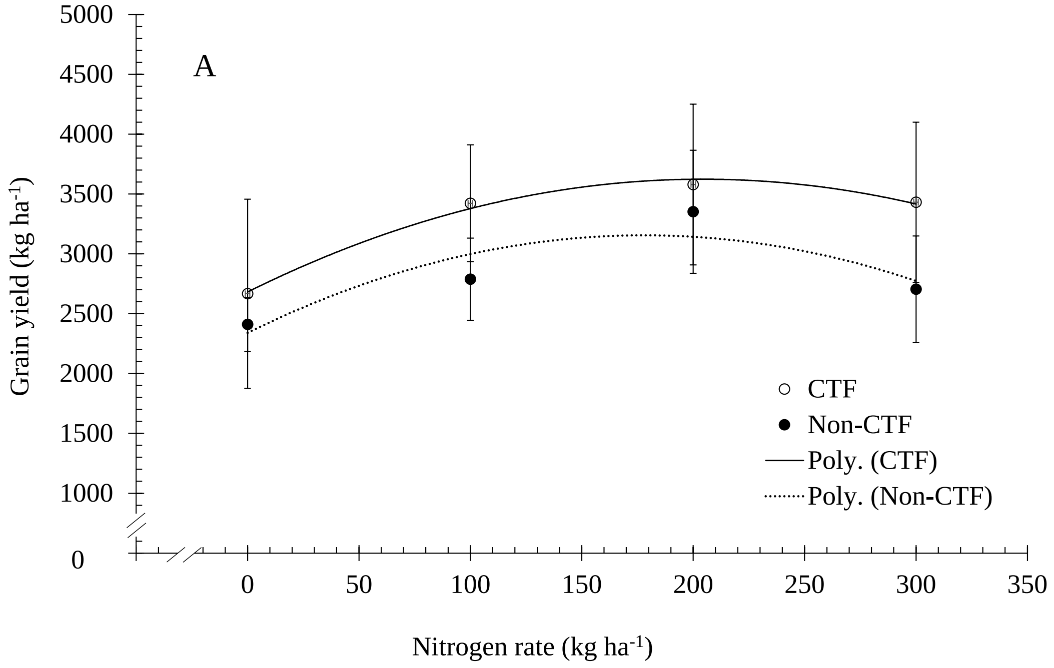


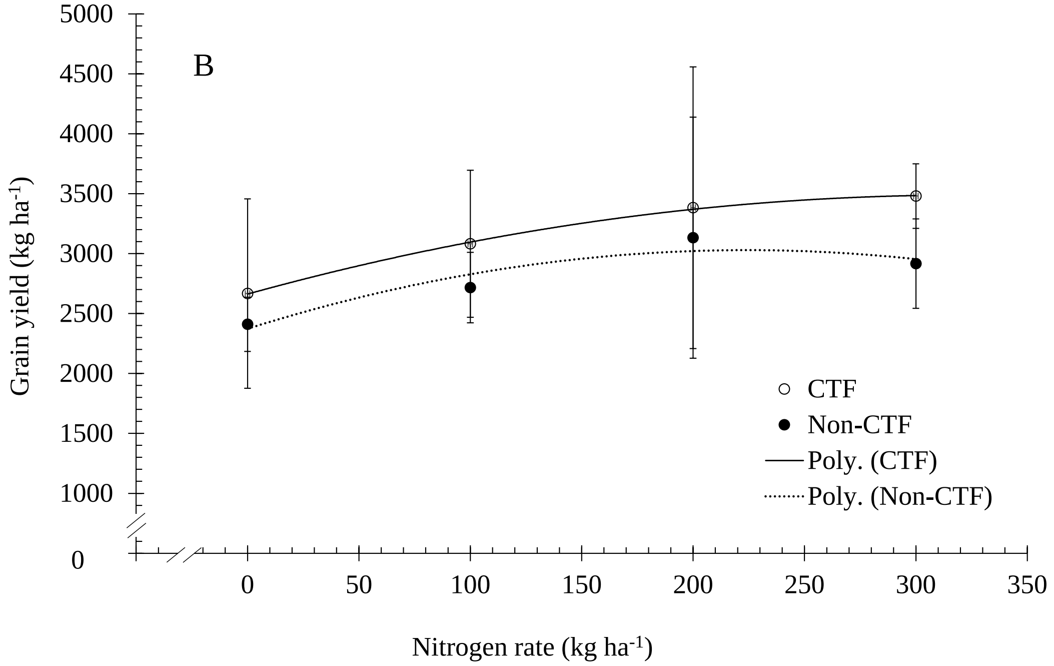
Figure 3.5. Relationship between infiltration rate (I_t, mm h^{-1}) and time (t, h) recorded at the experimental site for the two traffic treatments. Use P<0.05.

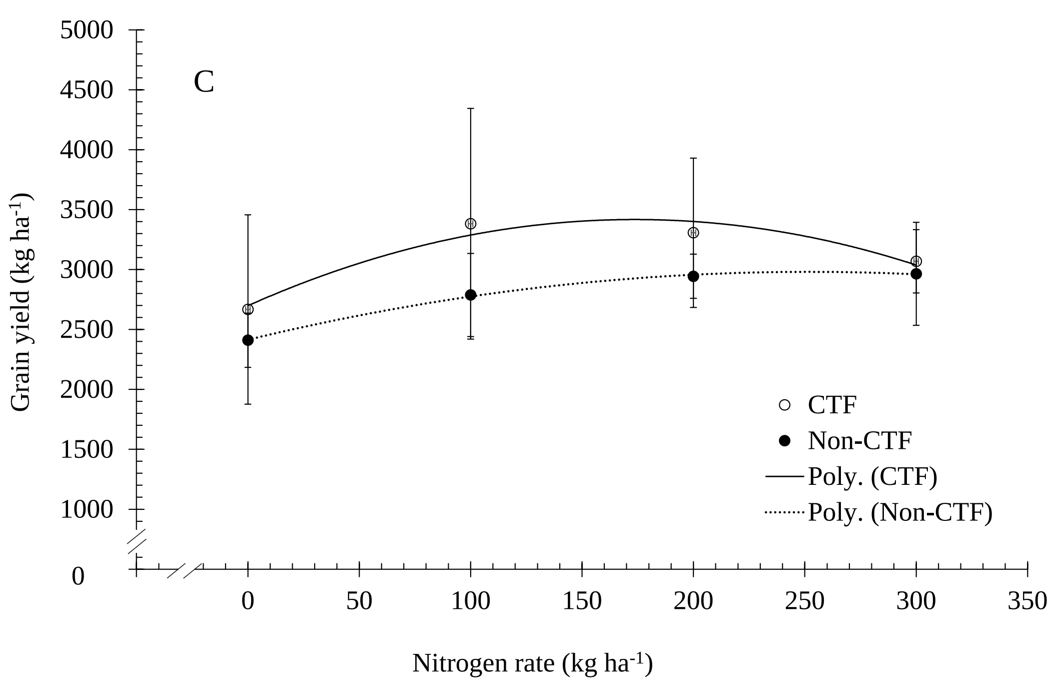
ii. Grain yield and yield components

There were significant differences in grain yield between CTF and non-CTF as well as between fertiliser-treated crop and controls (zero-N), which were observed in both traffic systems (P-values <0.05) (**Figure 3.6 d**). Comparisons between non-fertilised crops showed that grain yield was approximately 250 kg ha^{-1} higher in CTF compared with non-CTF (P<0.05). For fertiliser-treated crop, grain yield was approximately 400 kg ha^{-1} (≈12%) higher in CTF compared with non-CTF (P<0.05). The optimum nitrogen (N) application rates (MERN), and corresponding grain yields, were 122 and 3336 kg ha^{-1}, and 108 and 2887 kg ha^{-1} for CTF and non-CTF, respectively. Overall, there was not fertiliser type effect on grain yield, which suggested that compaction was the main factor influencing the response to applied N fertiliser. Thus, grain yield was significantly more sensitive to soil compaction than it was fertiliser N formulation. This effect was consistent at any given rate of N fertiliser. There was not fertiliser type

× N application rate effect on grain yield, which was observed in both traffic treatments (P>0.05) (Figure 3.6 a, b, c).







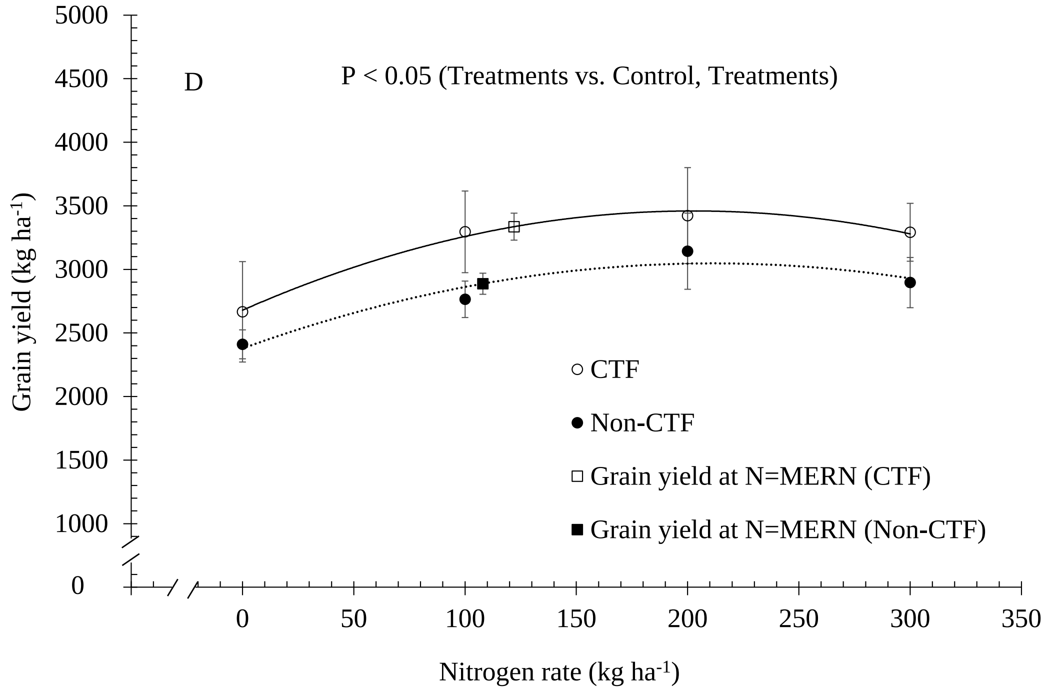
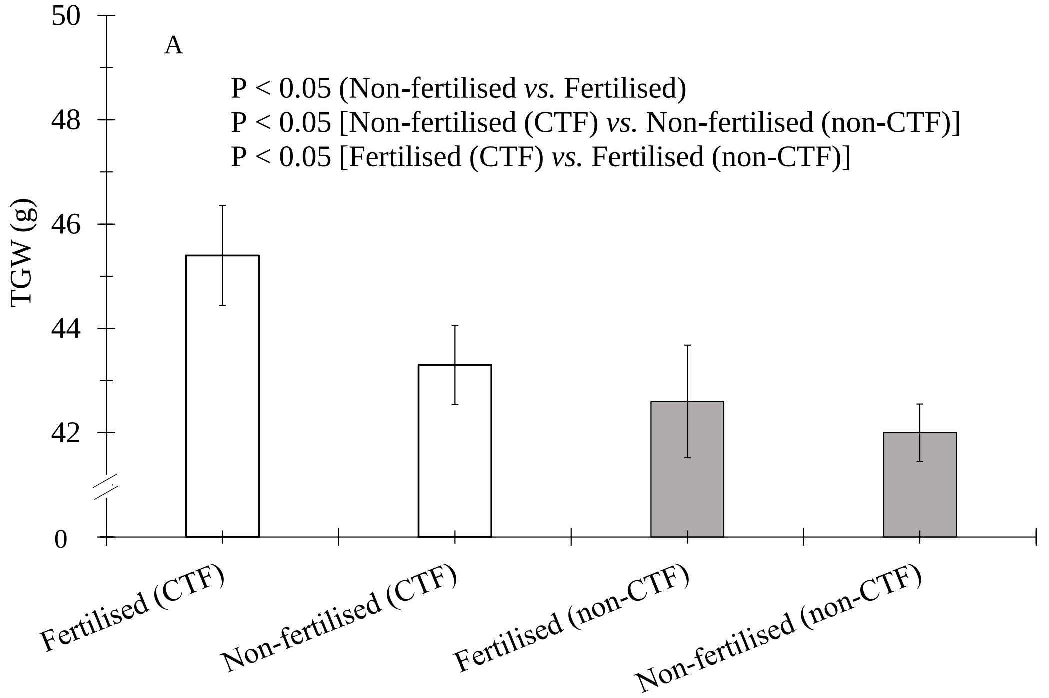


Figure 3.6. The relationship between nitrogen application rate and grain yield of wheat for UAN (A); ENTEC (B); urea (C); and summary of the three fertiliser formulations (D) for the traffic treatments representing by CTF and non-CTF, respectively. Error bars denote standard deviation (Std.) of the mean (n = 3 for A, B, C; whereas n=9 for D). For N = 0 and N=MERN, n = 3). Control (N = 0), treatments ($N \neq 0$).

Thousand grain weight (TGW), number of spikes and number of grains per m^2 showed significant differences between the traffic treatments (P-values<0.05), and therefore were consistent with relative differences in grain yield (**Figure 3.7**). The difference in TGW between non-fertilised of CTF (43.3 ± 0.76 g) and non-fertilised of non-CTF (42 ± 0.55 g) was also significant (P<0.05). There were significant differences in aboveground biomass between fertiliser-treated crop and controls, which were observed in both traffic treatments (P<0.05). However, studied yield components including biomass, TGW, HI and number of grains per m^2 were not significantly affected by fertiliser formulation (P>0.05) as shown in **Table 3.2**.

Table 3.2. Effect of traffic and fertiliser treatments on the yield components for wheat. Standard deviation (Std.) of mean (n = 3).

Traffic	N rate	Biomass (kg ha^{-1})			Thousand grain weight (g)			Harvest Index (%)			Number of grains per m^2		
		UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea
CTF	0	5439	5439	5439	43	43	43	48.8	48.8	48.8	7755	7755	7755
	100	6692	6145	6630	45	46	45	51.0	49.9	51.9	9941	10954	9003
	200	6984	6419	6711	45	45	46	51.1	52.2	49.7	8904	10361	11278
	300	6779	6689	5900	47	46	45	50.5	52.1	50.3	9150	9427	8142
	Mean	**6473**	**6173**	**6170**	**45**	**45**	**45**	**50**	**51**	**50**	**8938**	**9624**	**9044**
	Std.	**700.40**	**537.42**	**608.60**	**1.63**	**1.41**	**1.26**	**1.07**	**1.68**	**1.31**	**903.80**	**1395.70**	**1577.39**
non-CTF	0	5136	5136	5136	42	42	42	47.3	47.3	47.3	6108	6108	6108
	100	5123	5718	5768	42	42	42	55.6	47.7	48.7	5479	8168	7292
	200	5963	6479	5529	43	44	43	56.1	47.8	53.3	8725	8312	4539
	300	6057	5939	6230	41	42	43	45.4	49.3	50.6	7026	7772	7666
	Mean	**5570**	**5818**	**5666**	**42**	**43**	**43**	**51**	**48**	**50**	**6835**	**7590**	**6401**
	Std.	**510**	**556**	**458**	**1**	**1**	**1**	**6**	**1**	**3**	**1411**	**1014**	**1408**



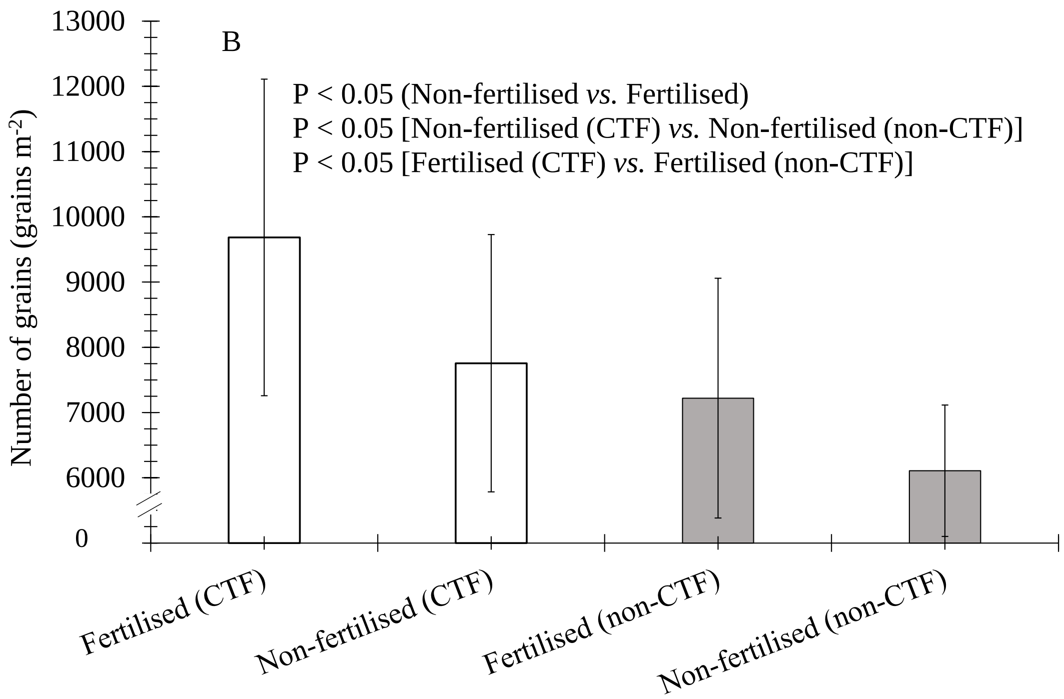


Figure 3.7. Thousand grain weight (TGW), and (B) number of grains per m^2 for wheat as affected by CTF and non-CTF treatments. Error bars denote standard deviation (Std.) of mean [n = 27 (fertilised), except for N=0 (non-fertilised), n = 3].

Overall, cumulative aboveground dry biomass was higher in CTF compared with non-CTF, which also reflected an enhanced response to applied fertiliser-N in the absence of traffic compaction (**Figure 3.8**). Traffic treatment effects on aboveground biomass were significant after tillering, which also explained the difference in dry matter accumulation throughout the crop cycle and dry matter partitioning. There was a N rate effect (P<0.10) on cumulative aboveground biomass, which was only observed after flag leaf.

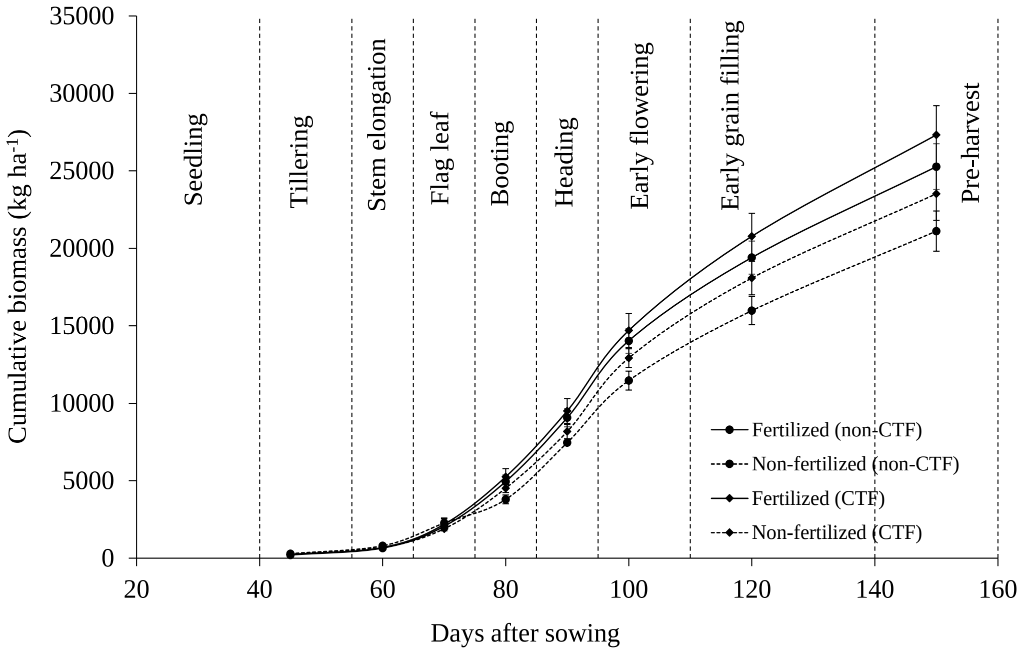


Figure 3.8. The effect of traffic treatments on cumulative aboveground biomass of wheat. Error bars denote standard deviation (Std.) of the mean. Crop growth stages are based on Zadoks et al. (1974). Use n = 27 for treatments (fertilised) and n = 3 for controls (non-fertilised).

Differences in harvest index (HI) were generally small (≤4%) and not affected by traffic treatment, fertiliser type or N application rate (P-values >0.05). despite the differences in HI were not significant, were consistent with the relative difference in grain yield and total aboveground biomass (**Figure 3.9**). Harvest indices were non-significantly higher when fertiliser was applied 100 and 200 kg ha^{-1} N (P>0.05), which was in accord with estimates of optimum N application rates.

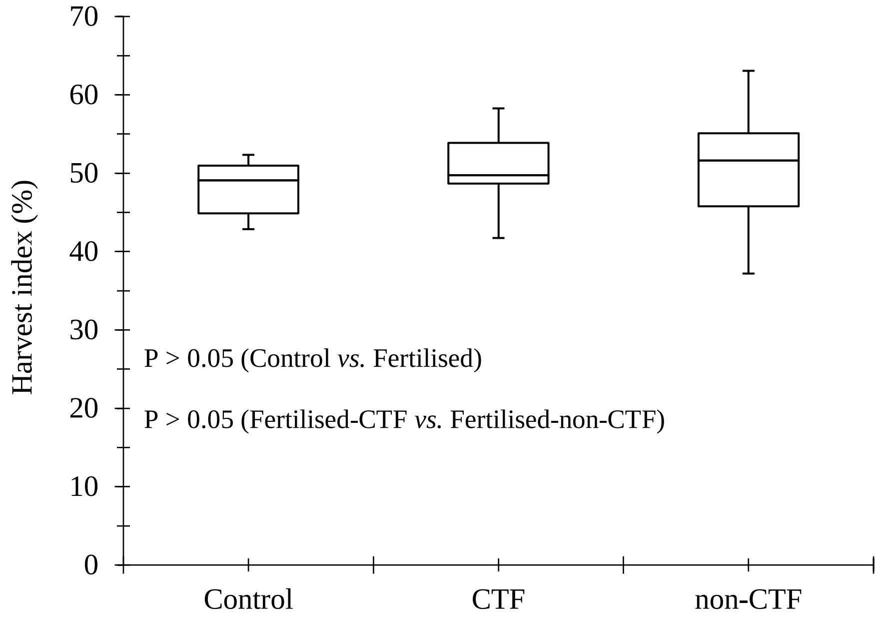


Figure 3.9. Harvest index for wheat as affected by CTF and non-CTF. Box plots show Min, Q1, Med, Q3, and Max, respectively. Use n = 6 for control (N = 0), and n = 27 for traffic-fertilised (N ≠ 0).

iii. Total grain nitrogen, Nitrogen uptake and nitrogen fertiliser use efficiency

Total grain-N was significantly higher in CTF compared with non-CTF (P<0.05). Overall differences in total-grain-N between traffic treatments were approximately 6%. Nitrogen contents were approximately 10% lower in controls compared with fertiliser treatments. These differences were consistent with grain N uptakes in grain, which showed up to 20% increase in NUE in CTF compared with non-CTF (**Figure 3.10**).

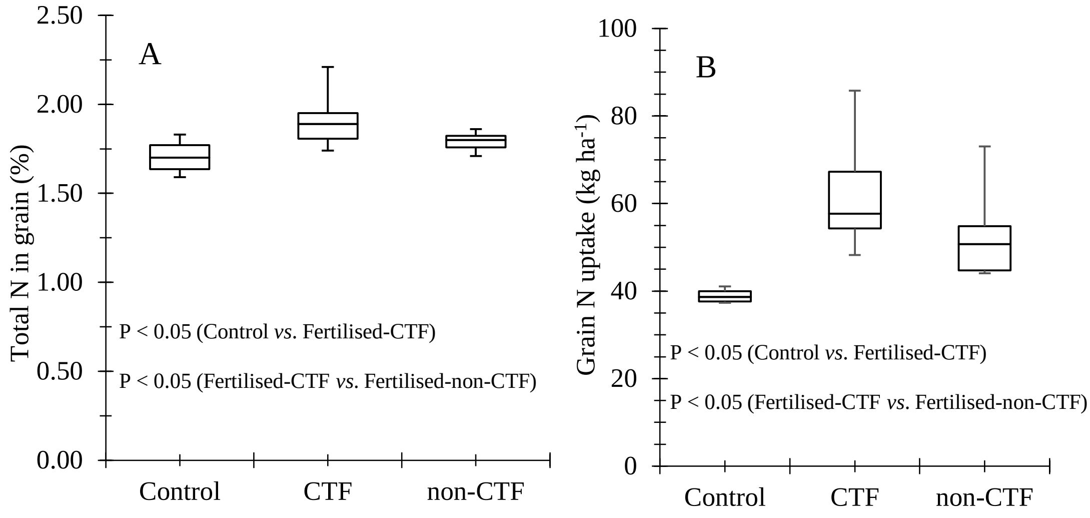


Figure 3.10. Traffic treatment effects on total N in grains (A), and N uptake in grain (B) for wheat. Box plots show: Min, Q1, Med, Q3, and Max, respectively. Use n = 6 for control (N = 0), and n = 27 for traffic-fertilised (N ≠ 0).

Traffic treatments representing the CTF system showed that N use efficiency (NUE) may be increased by up to 45% compared to non-CTF, which was significant (P<0.01) as shown in **Figure 3.11**. The fertiliser type effect was not significant (P>0.05) and confirmed a significantly greater effect of compaction on NUE (**Table 3.3**). This also suggested that significant improvements in NUE may not be possible if changes in fertiliser formulations are not concurrent with improved soil structural conditions which are achieved when field traffic is available. The value of NUE that corresponds with the most economic rate of N (MERN) was derived from the N use efficiency of nitrogen application rate response relationships shown in **Figure 3.11**. This shows that if N was to be applied at MERN, NUE is expected to be approximately 60% higher in CTF compared with non-CTF.

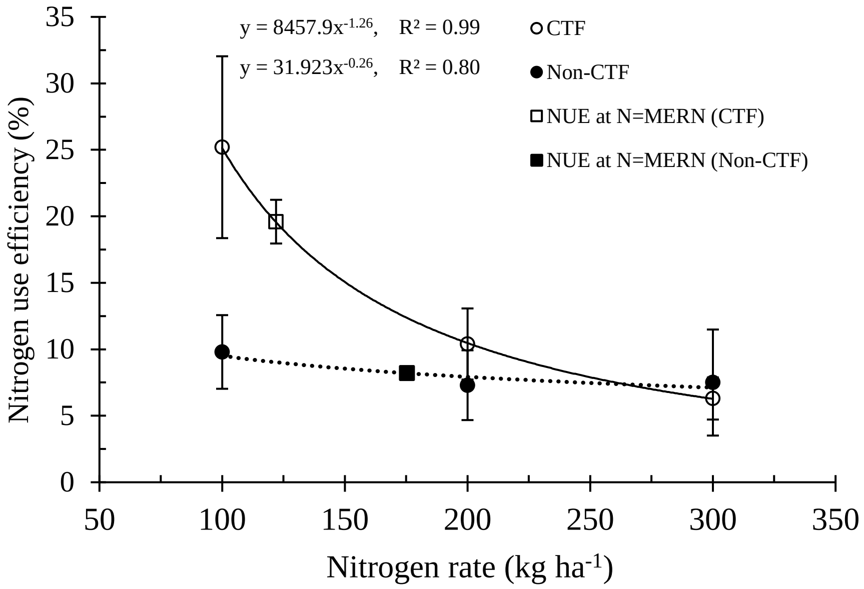


Figure 3.11. The relationship between N application rate and N use efficiency (NUE) for wheat under CTF and non-CTF treatments. Error bars denote Std. of mean (*n* =6, except *n* = 3 for N = 300 kg ha^{-1} and N=MERN). Use P<0.05.

Overall, agronomic efficiency (AE) was ≈35% higher in CTF compared with non-CTF (≈4 vs. 3 kg kg^{-1}, respectively), as shown in **Figure 3.12**. However, at the optimum N rate (MERN), the agronomic efficiency was approximately 50% higher in CTF compared with non-CTF (P<0.01). There was no fertiliser type effect on AE, which was therefore consistent with NUE calculations (**Table 3.3**).

Table 3.3. Effect of traffic treatment and fertiliser formulation on wheat crop responses to nitrogen.

Traffic	Fertiliser type	Total grain-N	Grain N uptake	NUE	AE
		(%)	(kg ha^{-1})	(%)	(Kg Kg^{-1})
CTF	UAN	1.83	59	14	4.9
	ENTEC	1.84	67	14	3.5
	Urea	2	59	25	3.8
non-CTF	UAN	1.83	49	11	3.2
	ENTEC	1.79	57	7	2.8
	Urea	1.75	48	8	2.9

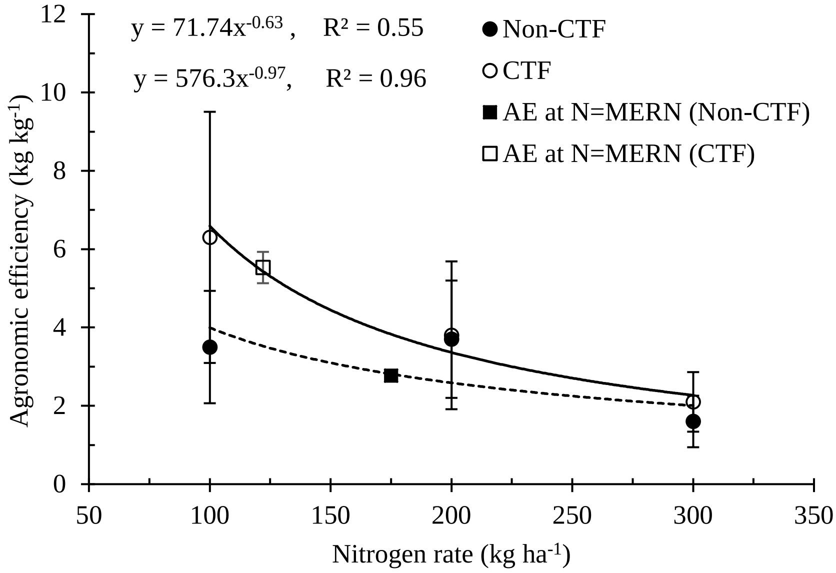


Figure 3.12. The relationship between N application rate and agronomic efficiency (AE) for wheat under CTF and non-CTF. Error bars denote Std. of mean (n=9, except n = 3 for N = MERN). Use P<0.05.

3.3.2. Sorghum

i. Soil physical and hydraulic properties

Soil penetration resistance for traffic treatments representing CTF and non-CTF systems is shown in **Figure 3.13**. Overall, there were significant differences ($P<0.05$) in penetration resistance between CTF and non-CTF, particularly in the 50 to 300 mm depth interval, where penetration resistance was up to 60% higher in non-CTF. The experimental site was intensively used for research purposes for many years which may have created such compaction (below 300 mm) that cannot be reached and removed by the subsoiler. Mean values of cone index in the 0-500 mm depth range were 2.5 and 5.1 MPa (LSD 5% level: 1.32) for the CTF and non-CTF treatments, respectively. This parameter has gradually increased in the wheeled and non-wheeled plots with increases in soil depth, particularly at 0-300 mm depth. This observation was consistent with the pattern of bulk density (**Table 3.2**). Differences in soil moisture content (w w^{-1}) between the two traffic treatments were not significant at all depth intervals (P>0.05).

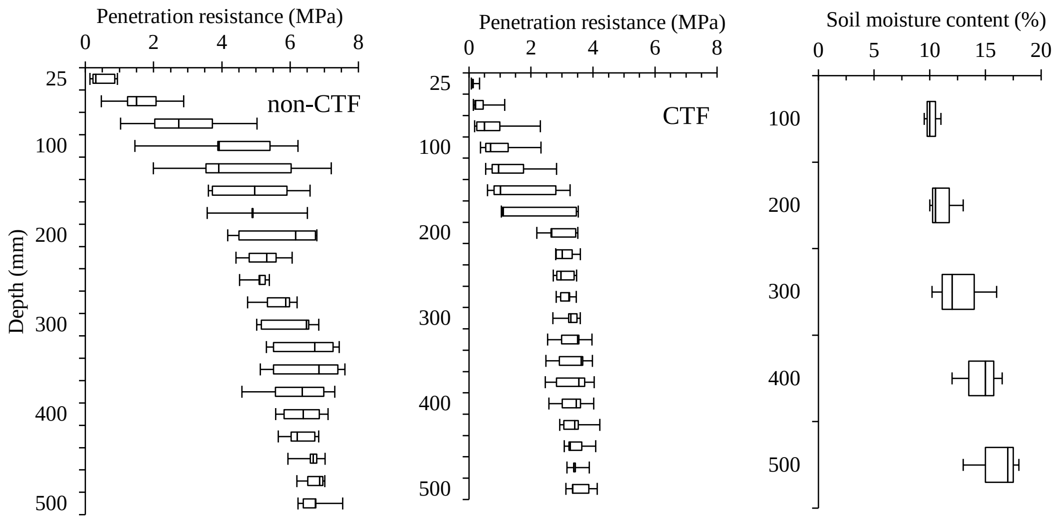


Figure 3.13. Soil penetrometer resistance profile in the treatments representing CTF and non-CTF for sorghum, respectively, and moisture content. Box plots show Min, Q_1, Med, Q_3, and Max, respectively. Use n = 10 for cone index and moisture content.

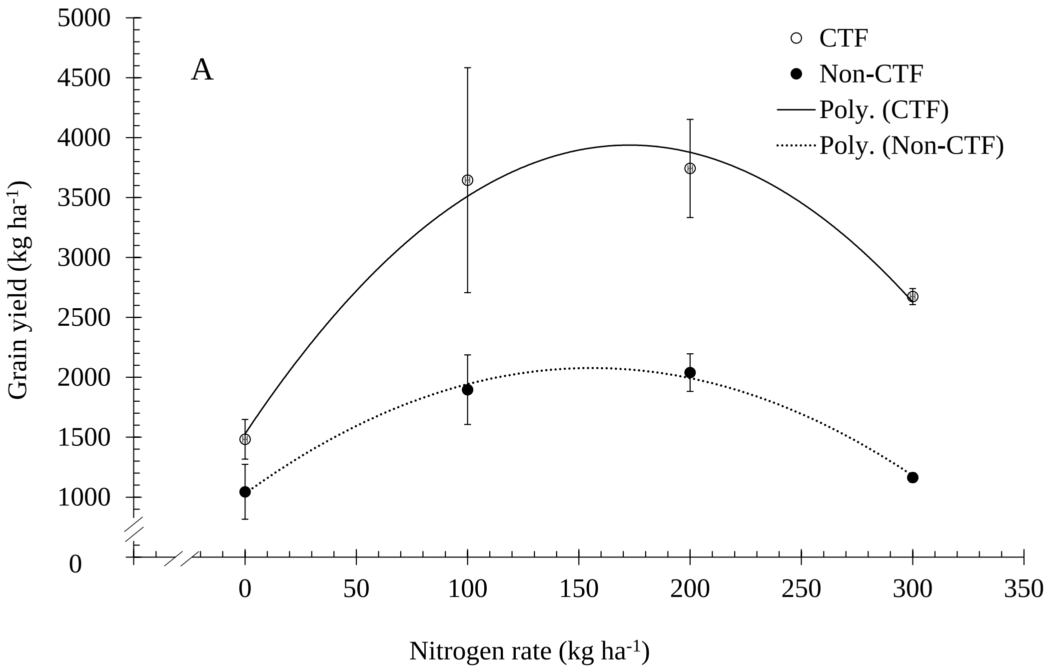
Table 3.4. Soil bulk density under CTF and non-CTF, The standard deviation (Std.) is shown as ± the mean value (n = 3). K_{SAT}: saturated hydraulic conductivity.

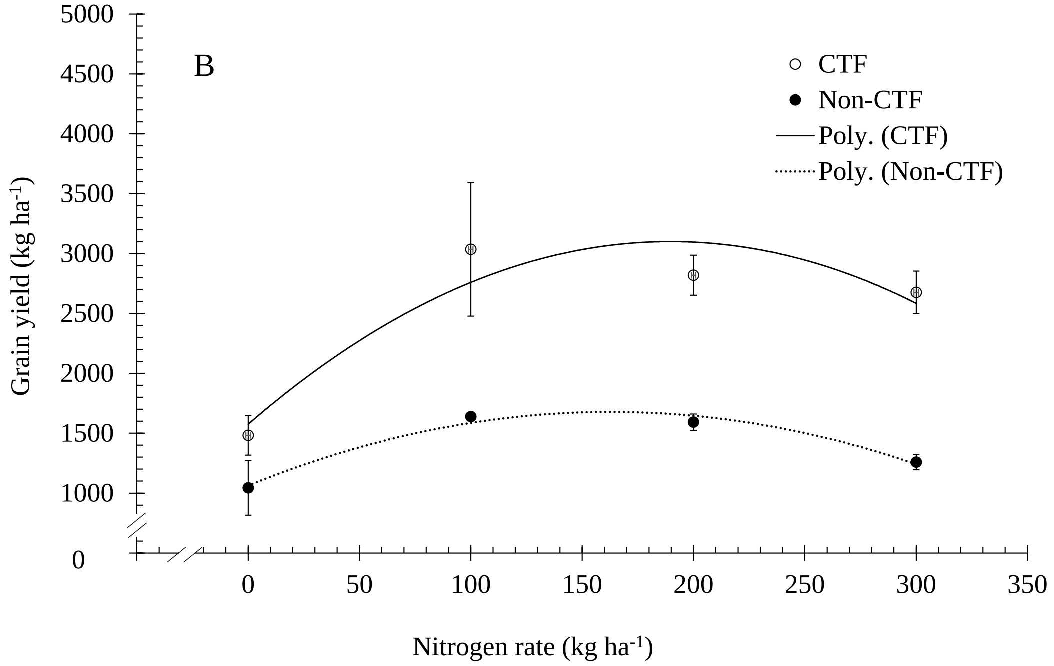
Traffic system	Depth	Bulk density	Total porosity	K_{SAT}
	(mm)	(g cm^{-3})	(%)	(mm day^{-1})
CTF	0-150	1.22±0.06	54±0.02	1000±6.65
	150-300	1.20±0.03	55±0.02	500
non-CTF	0-150	1.37±0.05	49±0.01	50±0.08
	150-300	1.38±0.04	48±0.01	25

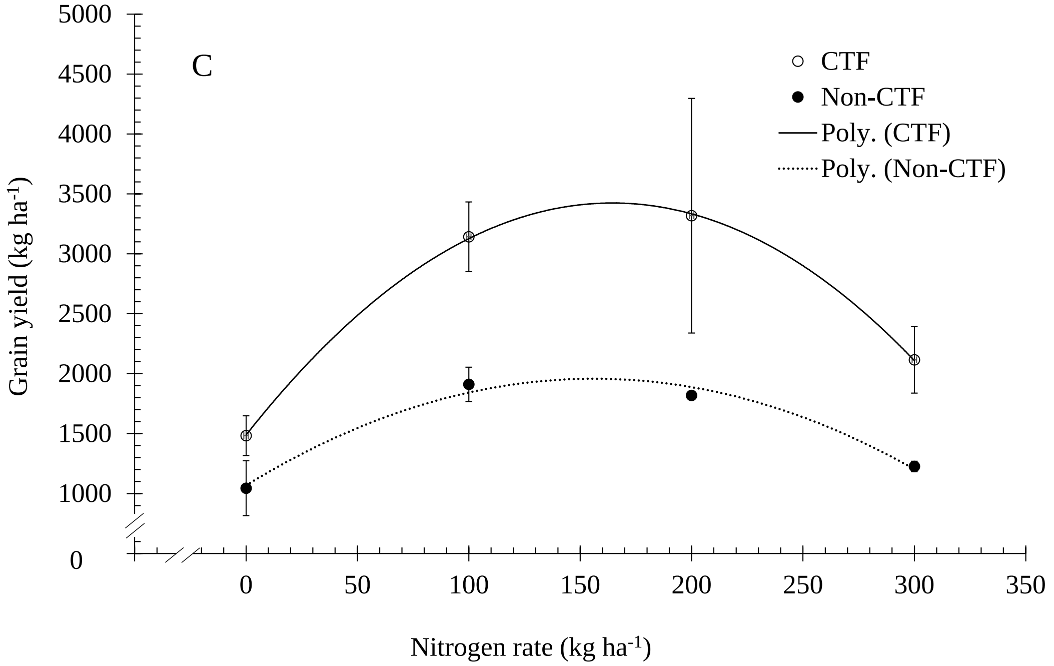
ii. Grain yield and yield components

There were significant differences in grain yield and yield components between the two traffic treatments as well as between fertilised (treated) and non-fertilised crop (controls), which were observed in both traffic systems (P<0.05). Yield components were also significantly affected by the traffic treatment and N application rate ($P < 0.05$).

Comparisons between controls showed that mean grain yield was about 480 kg ha^{-1} greater in CTF compared with non-CTF ($P < 0.05$). On average, the fertilised crop under the CTF treatment was approximately 1400 kg ha^{-1} higher compared with non-CTF ($P < 0.05$). The most economic rate of nitrogen (MERN), and corresponding grain yields, were 145 kg ha^{-1} N and 3428 kg ha^{-1}, and 100 kg ha^{-1} N and 1796 kg ha^{-1} for CTF and non-CTF, respectively. The fertiliser type effect on the grain yield and yield components was not significant ($P > 0.05$), which suggested that compaction was the main factor influencing the response to applied fertiliser N (**Figure 3.14d**) and **Table 3.5**. Thus, grain yield was significantly more sensitive to soil compaction than fertiliser N formulation. This effect was observed at any given rate of N fertiliser applied to crop (**Figure 3.14a, b, c**).




B
CTF
Non-CTF
Poly. (CTF)
Poly. (Non-CTF)
Grain yield (kg ha-1)
5000
4500
4000
3500
3000
2500
2000
1500
1000
0
0
50
100
150
200
250
300
350
Nitrogen rate (kg ha-1)


C
CTF
Non-CTF
Poly. (CTF)
Poly. (Non-CTF)
Grain yield (kg ha-1)
5000
4500
4000
3500
3000
2500
2000
1500
1000
0
0
50
100
150
200
250
300
350
Nitrogen rate (kg ha-1)

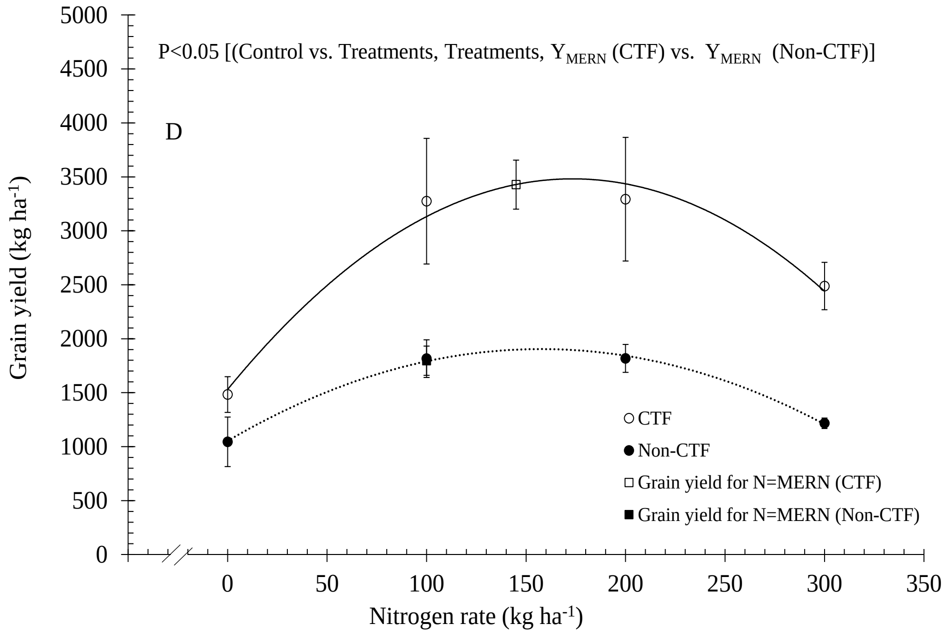


Figure 3.14. The relationship between nitrogen application rate and grain yield for sorghum for UAN (A); ENTEC (B); urea (C); and summary of the three fertiliser formulations (D) for the traffic treatments representing by CTF and non-CTF, respectively. Error bars denote standard deviation (Std.) of the mean (n = 3 for A, B, C; whereas n=9 for D). For N = 0 and N=MERN, n = 3). Control (N = 0), treatments (N $\neq$ 0).

There were significant differences in aboveground dry biomass (measured at harvest) between fertilised crop and controls, which were observed in both traffic treatments (P<0.01). The comparison between fertilised-CTF and fertilised-non-CTF was also exhibited to be significant (P<0.05) (8140 kg ha^{-1} for CTF vs. 5989 kg ha^{-1} for non-CTF) (**Figure 3.15 a**). The N application rate had also a significant effect on biomass (P<0.05). Overall, the average aboveground biomass was 28% higher in CTF compared with non-CTF treatments.

Differences in harvest index between fertilised and controls were significant in both traffic treatments as well as between the mean values under CTF and non-CTF, respectively (P<0.05). Harvest indices were higher when fertiliser was applied at the rate of 200 kg ha^{-1} N, which was in accord with estimates of optimum N application rates (**Figure 3.15b**).

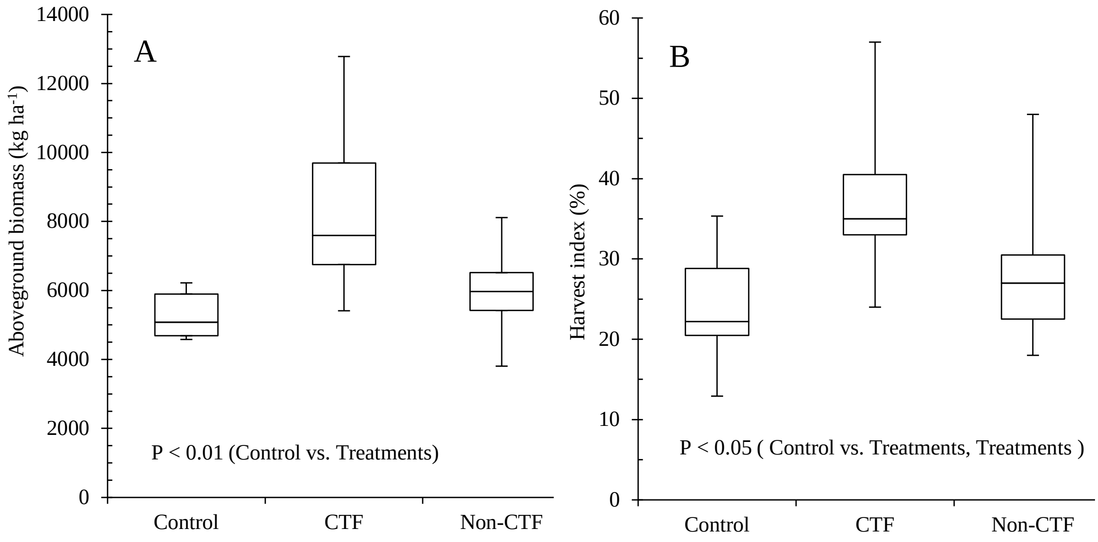


Figure 3.15. Aboveground biomass (A), and harvest index (B) for sorghum as affected by the traffic treatments representing by CTF and non-CTF, respectively. Box plots show Min, Q1, Med, Q3, and Max, respectively. Use $n = 6$ for control (N = 0), and $n = 27$ for traffic treatments (N ≠ 0).

Table 3.5. Effect of traffic and fertiliser treatments on the yield components of sorghum. Standard deviation (Std.) of mean (n = 3).

Traffic	N rate	Biomass (kg ha^{-1})			Thousand grain weight (g)			Harvest Index (%)		
	(kg ha^{-1})	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea
CTF	0	5865	5865	5865	22	22	22	26	26	26
	100	9358	8338	7264	23	22	22	37	40	37
	200	8113	9230	7378	23	23	22	46	31	36
	300	8502	8651	6427	22	22	21	37	36	33
	Mean	**7960**	**8021**	**6734**	**22**	**22**	**22**	**36**	**33**	**33**
	Std.	**1490.19**	**1484.09**	**717.63**	**0.73**	**0.33**	**0.53**	**8.06**	**6.17**	**5.04**
non-CTF	0	4693	4693	4693	19	19	19	22	22	22
	100	6721	6029	5067	20	21	22	28	25	29
	200	6710	6193	5006	22	20	21	34	32	36
	300	6612	5420	6141	19	22	20	23	20	23
	Mean	**6184**	**5584**	**5227**	**20**	**21**	**20**	**28**	**26**	**29**
	Std.	**995.21**	**680.48**	**631.28**	**1.20**	**1.35**	**1.23**	**5.52**	**5.70**	**6.17**

iii. Total grain nitrogen, Nitrogen uptake and nitrogen fertiliser use efficiency

Total N in grain was significantly higher in fertiliser-treated crop compared to control in both traffic treatments (P<0.05), but the difference between the two traffic treatments was not significant (P>0.05) (**Figure 3.16 a**). On average, nitrogen content levels were observed to be about 10% significantly lower in controls compared to fertilised crop for both traffic treatments (P<0.05). The differences in total grain-N were consistent with grain N uptake, which observed in the CTF up to 45% higher compared with non-CTF, and 60% compared to controls (**Figure 3.16 b**).

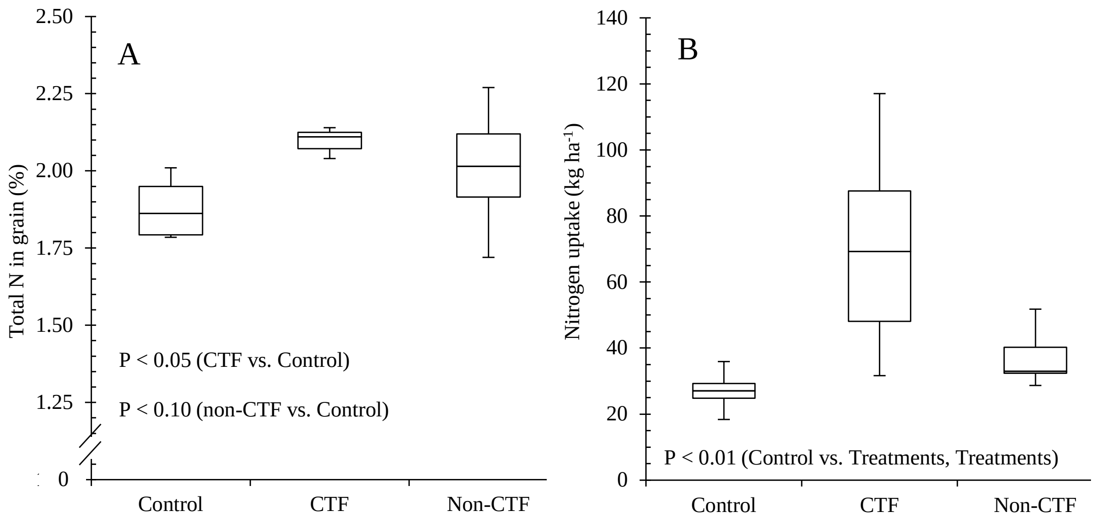


Figure 3.16. Traffic treatment effects on total grain-N (A) and grain N uptake (B) for sorghum, respectively. Box plots show: Min, Q1, Med, Q3, and Max, respectively. Use n = 6 for control (N = 0), and n = 27 for traffic treatments (N ≠ 0).

The traffic treatments had significant effects on nitrogen use efficiency (NUE) (P<0.05), and this value was higher by up to 60% in CTF compared with non-CTF as shown in **Figure 3.17**. The effect of fertiliser type was not significant (P>0.05) and confirmed a significantly greater effect of compaction on NUE. The value of NUE that corresponds with the optimum N application rate was derived from the nitrogen use efficiency-to-N rate response relationships shown in **Figure 3.17**. This shows that if

N was to be applied at the optimum rate (MERN), NUE is expected to be approximately 45% higher in CTF compared with non-CTF.

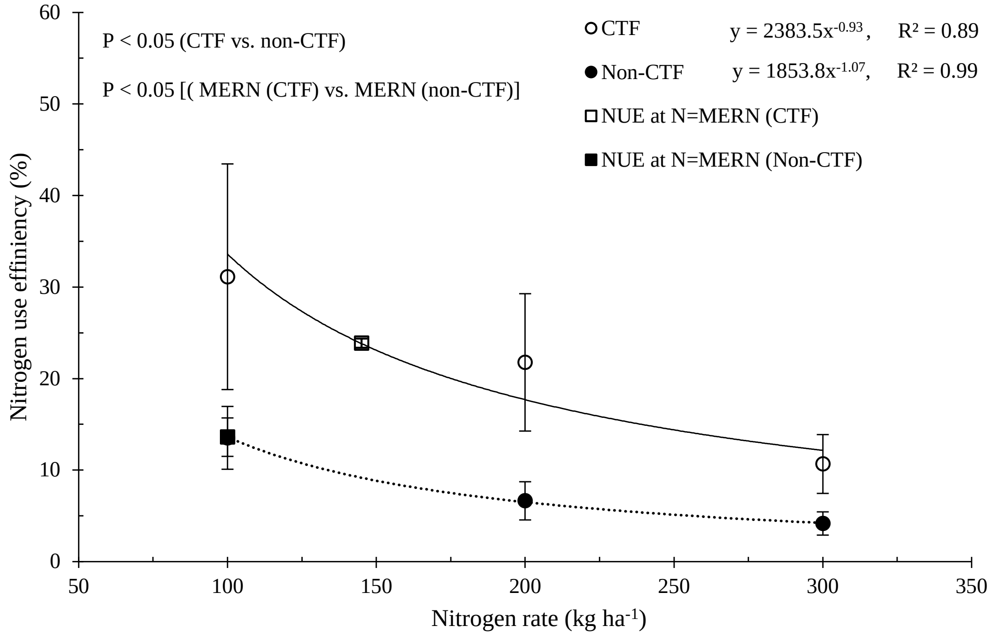


Figure 3.17. The relationships between N application rate and N use efficiency for sorghum under CTF and non-CTF treatments, respectively. Error bars denote standard deviation (Std.) of means. Use *n* = 9 (except *n* = 3 for N=300 and N=MERN).

Agronomic efficiency (AE) was approximately 60% higher in CTF compared with non-CTF (10 *vs.* 4 kg kg^{-1} for CTF and non-CTF treatments, respectively), as shown in **Figure 3.18**. However, the agronomic efficiency at the most economic rate of N (MERN) was insignificantly higher by up to 15% in CTF compared with non-CTF (P>0.05) (≈ 11.5 vs. 9.6 kg kg^{-1}, respectively). The fertiliser type was not significantly effected on AE, which was therefore consistent with NUE calculations **(Table 3.6)**.

Table 3.6. Effect of traffic treatment and fertiliser formulation on sorghum responses to nitrogen.

Traffic	Fertiliser type	Total grain-N	Grain N uptake	NUE	AE
		(%)	(kg ha^{-1})	(%)	(Kg Kg^{-1})
CTF	UAN	2.1	93	29	12.29
	ENTEC	2	61	23	8.74
	Urea	2	69	27	9.29
non-CTF	UAN	2	40	12	4.63
	ENTEC	2	32	7	3.12
	Urea	1.9	38	12	4.38

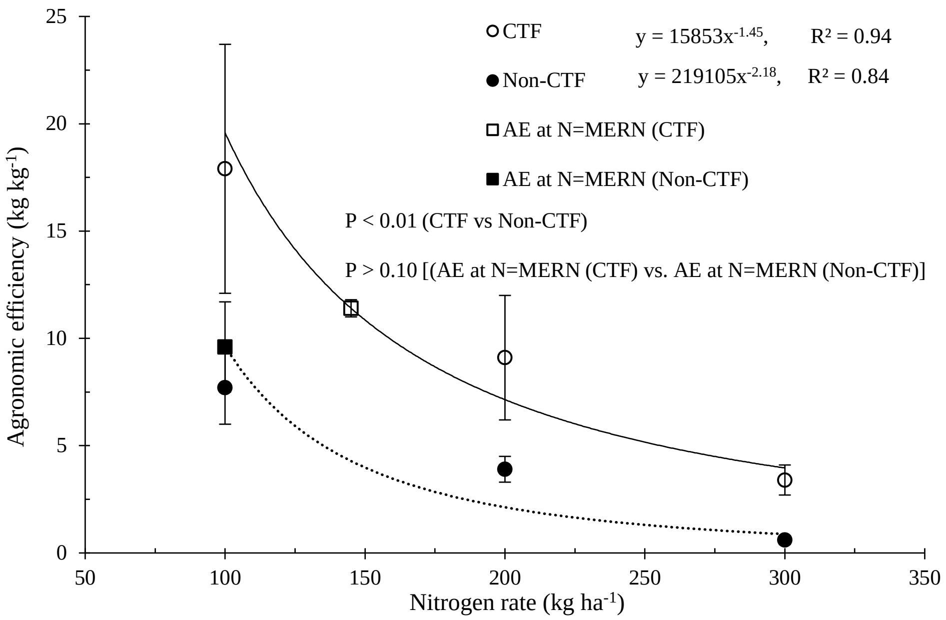


Figure 3.18. The relationships between nitrogen application rates and agronomic efficiency for sorghum under CTF and non-CTF systems. Error bars denote standard deviation (Std.) values at *n* = 9 (except *n* = 3 for N=MERN).

3.4 Discussion

3.4.1. Effect of soil compaction on soil and hydraulic properties

The ability of soil under CTF conditions to store more water was attributed to the greater infiltration rate (approximately double those of the non-CTF), and hydraulic conductivity (20 times higher in CTF compared to non-CTF). These results are consistent with observations reported by Antille et al., (2016b), which indicated that hydraulic conductivity was up to ten times higher in non-trafficked soil compared with trafficked soil. Data observed in the modelled runoff was 45% higher in non-CTF system compared with CTF treatment, particularly in the wetter years (>70th percentile; average rain = 1249 mm/season). This observation emphasised that CTF treatment is more able to hold water than non-CTF. This attributed to the smaller size of pores and fewer natural channel in compacted soils, which was represented by non-CTF system (Fleige and Horn, 2000).

Soil cone index was consistent with the soil bulk density, however, cone index samples were collected at moisture contents ranged 10-16% (w w^{-1}), which were below the optimum moisture content (21.2%) based on the Proctor test. Proctor density values obtained in this work (1.7 g cm^{-3}) suggested that soil susceptibility to traffic compaction may be highest at moisture contents in the range of 20% to 30% (w/w). Therefore, the risk of soil damage due to compaction will be proportionally reduced when traffic occurs at moisture contents below the plastic limit (Cresswell et al., 2016). Soil penetration resistance increases with decreasing soil water content (Lipiec, 2002). Cone indices were relatively higher compared to the resulting bulk density which may be due to the higher amount of iron oxide contained in the Red soils (Moody, 1994). The iron oxides, together with smaller amounts of free aluminium oxides (Moody 1994) and relatively high organic matter contents (Oades 1995), give Ferrosols their strongly developed structure. Soil compaction is increasing soil bulk density - soil penetrometer resistance and decreasing soil water infiltration are signs of soil compaction (Horn et al. 1995; Hamza and Anderson 2003, 2005); which therefore, interactions of these three factors are important for crops to influence their yield and input use efficiency (Marshall and Tokunaga 2006). In this study, differences in infiltration rates and bulk density between the two traffic treatments are agree with observations of surface hydraulic properties of wheeled and non-wheeled soils (e.g., Li et al., 2009; Vero et al., 2014). These differences are attributed to traffic compaction leading to reduced soil porosity and disruption of pores connectivity, particularly between larger, vertically oriented drainage pores (Pagliai et al., 2004; Bhave and Sreeja, 2013).

3.4.2. Effect of compaction on grain yield and yield components

i. Wheat crop

Grain yield is usually affected by two main components, which are number and weight of grains (Slafer, 2003). Figure 3.7b shows that the number of grains per m^2 was significantly higher in CTF compared with non-CTF treatment, which was also confirmed by Slafer and Andrade (1993). Higher grain yields are expected in crops that accumulated have higher biomass at maturity (Austin, 1982). Total aboveground biomass at pre-harvest, thousand grain weight (TGW), number of spikes and number of grains per m^2 within this work showed significant differences between traffic treatments, which therefore demonstrate differences in grain yield. The response to compaction of these yield components reflects the crop’s sensitivity to such compaction and the impact on fertiliser use efficiency. This latter effect linked to rainfall use efficiency (Sadras and Rodriguez, 2010).

Harvest indices of treated (fertilised) plots observed in this experiment were in the range of the other studies (e.g., Sinclair, 1998; Dai et al., 2016). Relative reduction of grain yield with a further increment in applied N above 200 kg ha^{-1} might be attributed to vegetative growth early on in the season when both water and nutritional (N) conditions where not limiting (Table 3.2). Later in the season, even though N supply in the 300 kg/ha treatments was not limiting, water and temperature became the limiting factors. Therefore, a higher initial biomass in those plots could not sustain an equally high grain yield level. Consequently, grain yield was affected to greater extent in those plots compared to the plots where lower N rates were applied. By contrast, these plots developed a smaller biomass early on in the season, consistent with the N supplied via fertiliser, and required less water to satisfactorily complete the season. The end result is that both the water (rainfall) and N (fertiliser) were optimised at a lower than the maximum investigated in this experiment, and denotes a significant effect of water x N interaction on grain yield. These finding was confirmed by Gaju et al. (2014) who reported that the environmental factors greatly influencing pre-anthesis accumulation of N (e.g., drought and higher temperature during spring of wheat crops) and subsequent remobilization of N as the crop approaches the grain-filling phase. Zemichael et al., (2017) have reported a decrease in grain yield with the application of higher doses above 69 kg N ha^{-1} caused by excess vegetative growth, decreased number of grains per spike and delayed senescence that may have resulted in low rates of grain filling.

The agronomic efficiency (AE) (defines in Equation 3.7), decreased by approximately 48% and 62% (UAN), 15%, and 35% (ENTEC), and 55 and 81% (urea) for the high N increment (100-200 and 200-300 kg N ha^{-1}, respectively) under CTF treatment (Figure 3.6 a, b and c). These findings were relatively consistent with Lester et al.,

(2016) who used the same approach that applied in this study to measure AE. They reported that AE decreased by 40% (Kingaroy) and 20% (Kingsthorpe) for the higher N increment (80–120 or 80–160 kg N/ha at Kingaroy and Kingsthorpe, respectively) compared with the first 80 kg N/ha applied at each location. The current result conforms with that of Antille et al. (2017) who reported that AE decreased with increasing N rates from 50 to 250 kg N ha^{-1}. The reduction of nitrogen use efficiency (NUE) and AE in non-CTF treatments was attributed to water and nutrients stress due to limited access of roots to the subsurface soil layers, and thus the uptake of nitrogen was limited as well (Rashid et al., 2015). Despite the fact that the effect of field traffic on moisture content was not directly measured in my study, when compacted, soil undergoes changes in pore size and pore size distribution, which affect hydraulic conductivity and water retention. However, it was possible to confirm the adverse effects of compaction on soil water by examining the results derived from the APSIM modelling work. Specifically, the effects of compaction on increased runoff and reduced rainfall use efficiency. Fertiliser N recovery efficiency across region varied over a large range: 0.1 to 0.4 kg N taken up per kg N applied (10–40%) based on grain N alone (Ehdaie et al., 2010). Levels of fertiliser applications influence the grain yield and the total dry matter accumulation thereby affecting the nutrient demand (uptake/utilisation). Increasing applications of N from 0 to 300 kg ha^{-1} reduces overall N use efficiency and agronomic efficiency in wheat and sorghum. For wheat, nitrogen use efficiency at 300 kg ha^{-1} was 48% lower than 200 kg ha^{-1} for both traffic treatments. Such low N recoveries may be related to N losses from soil via denitrification, ammonia volatilization, and NO_3^--N leaching (Craswell and Vlek, 1979). Differences in NUE between treatments due to N uptake were also explained by both traffics effect on yield and total N in grain, as shown in Figure (3.10 and 3.11). The current result conforms with that of Antille et al. (2017) who reported that AE decreased with increasing N rates from 50 to 250 kg N ha^{-1}.

Despite this, there were no significant differences in NUE between the three N fertiliser types, NUE in both traffic treatments increased in the order: UAN > urea > ENTEC, which was consistent with differences in grain yield and yield components between the three fertiliser formulations. Relatively low rainfall received during the critical stages of plants (from July to the end of August) (**Figure 3.1**), affected grain yield negatively, particularly in compacted soil (Hakansson and Lipiec, 2000).

ii. Sorghum crop

Yield data have confirmed the existence of ‘yield reduction’ on the crop grown in a non-CTF system by up to 40% compared with CTF, which agreed with results reported by Chan et al., (2006) conducted in different soils and environment. They found that canola grain yield on the wheel track was only 34% of that recorded in between wheel tracks. The level of grain yield increase in non-compacted soil was within the range (30-55%) reported in numerous past studies (Radford et al., 2001; Hamza and Anderson, 2003; Sadras et al., 2005). Boone and Veen, (1994) attributed the poor agronomic performance in compacted soil to the limited supply of water, oxygen and nutrients from the soil to the root system or a limited activity of the root system. Similar findings were highlighted in the earlier study (Hussein et al., 2017) for wheat crop under the similar soil type and conditions. This study confirmed that the impact of fertiliser formulations was not significant which was also reported in the wheat study and also highlighted by Lester et al., (2016). However, both studies found that UAN had an insignificant grain advantage, especially at 200 kg ha^{-1} N compared with ENTEC and urea. Based on the grain yield (Fig. 3.14 a, b, c) and Table 3.6, sorghum grain yield was higher under UAN and urea compared to ENTEC (UAN > urea >

ENTEC). However, in the higher rates of N application (≥ 200 kg ha-1) sorghum response to ENTEC and UAN was higher compared to urea, particularly under non-CTF. This was consistent with the observations provided by Lester et al. (2016) who evaluated DMPP coated urea (ENTEC) and untreated urea in grain sorghum production systems with differing cropping intensities grown on two contrasting soil types (Ferrosol and Vertosol).They found that nitrification inhibitors added to urea can reduce gaseous losses (e.g., N2O emissions), particularly at higher N application rate. Whilst N2O has not been measured in our study, this provides a possible explanation. Nitrogen saved in emissions could have been used by the crop and translated into biomass and grain yield.

3.5 Conclusions

The main conclusions derived from **Chapter 3** are summarised below:

1. The crops response to N fertiliser rates indicated that nitrogen amounts required were less than the highest doses applied to both traffic systems. Fertiliser use efficiency increased by around 28% in winter wheat and 58% in sorghum as a result of reducing the required of N fertiliser rate in CTF system.

2. Grain yields, and crop-to-nitrogen response were more sensitive to soil compaction represented by traffic systems than fertiliser formulations, which confirmed that soil compaction is the main driver for the changes of crop-growth.

3. As a results of enhancing soil physical and hydraulic properties, crop performance was improved in CTF system by up to 12% and 45% in wheat and sorghum, respectively. Grain yields improvement by approximately 350 and 1300 kg ha^{-1}, respectively, were possible in CTF, which subsequently has

positive impact on the economic considerations, especially when zero-tillage is practised (demonstrated in **Chapter 5**).

4. MODELLING OF CROP PERFORMANCE

4.1. Introduction

The interaction between environmental factors with crop, soil and traffic have a significant influence on crop performance, soil function and soil water, because of the effect on runoff and availability of soil water (Tullberg et al., 2001). When investigating trends in historic grain yield and yield components data, it is difficult to separate the effects of climate on crop production from the effects of soil, cropping systems and management. The use of simulation model makes this research possible while keeping the other factors constant.

Decision-making and planning in agriculture increasingly rely on model-based decision support tools that are able to combine climatic variables with soil and crop-related parameters to simulate management scenarios. The crop performance simulation models commonly used are mechanistic, as they attempt to explain the relationship between-parameters and simulated variables, as well as processes (Nix, 1985; Porter and Semenov, 2005; Challinor et al., 2009). For predicting and capturing a yield performance of crops in relation to climate and soil factors, Agricultural Production Systems Simulator (APSIM) model was often used to achieve this aim (Keating et al., 2003) by simulating conditions conducted in **Chapter 3**. This model is a highly advanced simulator of agricultural systems and widely used in Australia. It contains a suite of modules, which enable the simulation of farming systems that cover a range of plant, animal, soil, climate and management interactions. APSIM is one of the few available dynamic, crop growth simulation models capable of dealing with water and N dynamics under different fertility management conditions (Akponikpè, et al., 2010). This farming system simulation framework is a well-validated cropping simulation program, and has been extensively and widely tested in a range of Australian environment (Asseng et al., 1998 a, b; Chenu et al., 2011; Peake et al., 2011), as well as in Europe and India (Asseng et al., 2000; Gaydon et al., 2011). The APSIM-Sorghum module (Hammer et al, 2010; Whish et al., 2005) and APSIM-Wheat module (Carberry et al., 2013; Holzworth et al., 2014b) have been broadly tested across soil and climate conditions in Australia and internationally for a range of experimental conditions with satisfactory results. For example, Carberry et al., (2009) investigated evaluation performance of APSIM model by simulating 17 years of wheat crop from around the Australia wheat belt and comparing the modelled versus observed grain yields. The outcomes of this work concluded that the modelling of crop performance simulated by APSIM was reliable when compared to the yield data obtained from the field experiments.

In Chapter 3, the two traffic systems were evaluated and studied in the field-scale for two seasons comprising wheat and sorghum, respectively. However, as a supplement to the previous evaluation of field measurements to assess the effects of the degree of compaction represented by two traffic systems, and integrated with different levels of N fertiliser, it was necessary in the present chapter to examine the long-term impacts of these factors on yield production and soil properties, in order to confirm the optimal cropping system that is able to maximise crop productions and improve soil conditions. Therefore, the objective reported in this chapter was to quantify the potential reduction in grain yield and yield components due to long-term effects of soil compaction (1955-2016), so as to be able to simulate relative effects of controlled and non-controlled traffic treatments, respectively.

4.2. Model description

Simulations were conducted using the Agriculture Production System Simulator (APSIM) farming systems model (Holzworth et al., 2014). Full documentation for APSIM's modules, mathematical structure and source codes can be found at www.apsim.info/documentation/. APSIM developed from two previous models, namely: PERFECT (Littleboy et al., 1992) and AUSIM (McCown and Williams, 1989). These two models were combined to produce (a) high sensitivity of crop models; (b) ability to simulate a wide range of configurations of crops. The APSIM modelling framework is made up of a set of several sub-models (modules) and elements including crop-pasture and forest, soil water balance and solute movement, soil organic matter and soil fertility proportions as well as erosion (Keating et al., 2003). The APSIM model is a software tool that enables these modules to communicate with each other through a central control unit named the 'Engine' to simulate agricultural systems.

4.2.1. Soil water balance and solute movement

In APSIM, there are two modules of water balance and solute movement. The first one is a cascading layer (SOILWAT: Probert et al., 1998 a) and the second one uses a numerical solution of Richard's equation (SWIM: Verberg et al., 1996a, b). Despite the modules being different, both techniques are interchangeable and work with all plant models. The plant modules simulate key underpinning physiological processes and operate on a daily time step in response to input daily weather data, soil characteristics and crop management actions.

i. SOILWAT module

SOILWAT is a cascading layer model that owes much to its precursors in CERES (Ritchie, 1972; Jones and Kiniry, 1986) and PERFECT (Littleboy et al., 1989, 1992). It operates on a daily time step. The water characteristics of the soil are specified in terms of the lower limit corresponding to a soil potential of 15 bar (LL15), drained upper limit (DUL) and saturated (SAT) volumetric water contents of a sequence of soil layers. The thickness of each layer can be specified by the user; normally the thickness of upper layers range from 100 to 150 mm and from 300 to 500 mm for the base of the profile; the whole profile might be including up to 10 layers. As with all layered models, the empirical soil parameters are influenced by the number and thickness of specified layers. SOILWAT operates on a daily time step, and typical of such models the various processes are calculated consecutively. The APSIM modules that can be communicated to the SOILWAT module include SoilN, Solute, Residue, and Crop. Processes represented in SOILWAT, adapted from a long history of 'cascading bucket' style water balances such as WATBAL (Keig and McAlpine, 1969) and CERES (Ritchie, 1972; Jones and Kiniry, 1986) include:

- Runoff from rainfall is calculated using a modified USDA-Soil Conservation Service procedure known as curve number approach (USDA, 1972), that include effects of precedent soil water content, soil cover both from crop and crop residue, and surface roughness, generally due to tillage. The technique utilises total precipitation from one or more storms events occurring on a given day to estimate runoff. Modified USDA curve number runoff model:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \textbf{(4.1)}$$

where: Q is runoff (mm), P is rainfall (mm), S is the retention parameters (mm).

- Evaporation is based on potential evapotranspiration and is calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (1972).
- Saturated water flow occurs when the soil water content (swcon) in any layer is below saturation (SAT) but above drained upper limit (DUL). A specified proportion (swcon) of the water in excess of DUL drains to the next layer.
- Unsaturated flow at water contents below DUL where gradients in soil water content occur between layers (e.g., in response to rainfall events or evaporation). Therefore, unsaturated water flow may occur towards the surface and downwards, but cannot move water out of the bottom of the deepest layer in the profile.
- Movement of solutes associated with saturated and unsaturated flow of water are calculated using a 'mixing' algorithm, which assumes that all water and solute entering or leaving a layer is completely mixed. The meaning of this concept is that solute movement can be calculated as the product of the water flow the solute concentration in that water.

ii. *SWIM module*

Soil Water Infiltration Movement (SWIM) is a software package developed within the CSIRO Division of Soils for simulating infiltration, evapotranspiration and redistribution. SWIM is based on a numerical solution of Richards' equation combined with the convection-dispersion equation to model solute movement. Its implementation in APSIM is based on the 'stand-alone' SWIMv2.1 (Verburg et al. (1996 a). SWIM has its own internal time step which is governed by the magnitude of water fluxes in the soil, i.e., larger fluxes lead to smaller time steps). Parameterisation of the soil water and properties (e.g., bulk density, porosity) for SWIM requires specification of the moisture content and hydraulic conductivity relationships in each soil layer. Runoff is dealt with by considering surface roughness. This capability to detain surface water can change through time, e.g., it may increase as a result of cultivation, or decrease due to the impact of raindrops. Infiltration into soils that seal or crust are dealt with through the conductance of an infinitely thin surface membrane. As for surface roughness, seal conductance can also be specified to vary in response to rainfall or tillage.

4.2.2. Crop module

APSIM includes an array of modules for simulating crop yield and phenological stages of development, pastures and forests, and their interaction with the soil. This model is able to simulate the influence of climate and soil conditions on the performance of a single crop or a cropping system. It also allows the evaluation of management intervention through tillage, irrigation or fertilisation as well as choice, timing and sequencing of crops, either in fixed or flexible rotations. Currently, APSIM is able to simulate more than 20 crops, and the crop modules are available for several crops including water and summer cereals (Robertson et al., 2002; Keating et al., 2003). For the requirements of this study, APSIM was configured with APSIM-Crop modules of Wheat (Asseng et al. 1998 a, b) and Sorghum (Hammer and Muchow 1991).

i. APSIM-Wheat module

APSIM-Wheat has been derived from a combination of approaches used in previous APSIM wheat modules: Asseng et al. (1998a, b); Wang et al. (2003); Meinke et al. (1997, 1998). The current version of the model is implemented within the APSIM Plant model framework, which is currently used for other crops such as grain legumes and canola. Most of the model constants (species-specific) and parameters (cultivar specific) are externalised from the code (wheat.xml file).

There are 11 phenological stages in the APSIM-Wheat module starting from sowing to the end of cropping. These phases are sowing, germination, emergence, stem elongation, flower initiation, the start of grain filling, end of grain filling, maturity, harvest, and the end of cropping. The timing of each stage (except from sowing to germination, which is driven by sowing depth and thermal time) is determined by the accumulation of thermal units (degree days) adjusted for other factors, which vary with the phase considered (e.g., vernalisation, photoperiod, N). The length of each phase is determined by a fixed thermal time (thermal time target T), which is specified by tt_<phase_name> in wheat.xml. Most parameters of thermal time targets are cultivar-specific. The daily thermal time (ΔTT) is calculated from the daily average of maximum and minimum crown temperatures, and is adjusted by genetic and environmental factors. Crown temperatures are simulated according to the original routines in CERES-Wheat and correspond to air temperatures for non-freezing temperatures. The maximum and minimum crown temperatures (*Tcmax* and *Tcmin*) are calculated according to the maximum and minimum air temperature (*Tmax* and *Tmin*), respectively.

ii. APSIM- Sorghum module

APSIM-Sorghum module was originally developed from QSORG model (Hammer and Muchow, 1991) with features of AUSIM model (Carberry and Arbrecht, 1991), but it has been extensively revised and improved since then, and recently adapted into the APSIM-crop module template (Wang et al., 2002). APSIM-Sorghum module simulates a sorghum growth in a daily time-step (based on an area). Sorghum growth in this model responds to climate (temperature, rainfall and radiation from the meteorological information module (Met module)), soil water supply (from the soilwat module) and soil nitrogen (from the soilN module). The sorghum module returns information on its soil water and nitrogen uptake to the soilwat and soilN modules on a daily basis for reset of these systems. There are 9 crop phases (time between stages) in the sorghum module, which are presented in the module structure below (**Figure 4.1**).

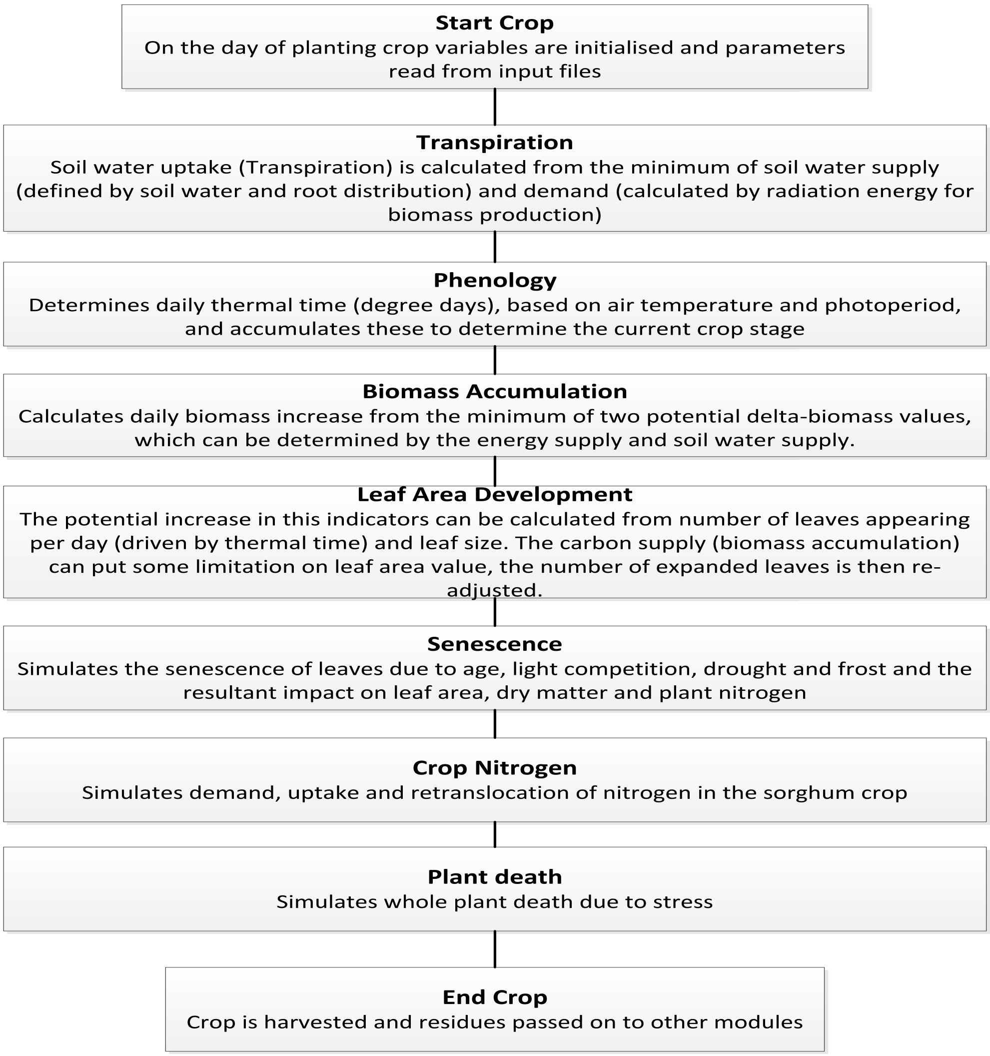


Figure 4.1. Order of key simulation steps in the sorghum module. Processes in daily loop.

4.3. Model calibration

Simulations involved dryland wheat and sorghum crops, grown in soils representing CTF and non-CTF traffic systems, respectively. The soil used in the simulations was Red Ferrosol, and were consistent with that used in the field studies, and simulations conducted on a continuous basis for 56 years (from1960 to 2015). The results were grouped as rainfall classes, which included the driest 30%, the wettest 30% and the average 40% years to determine the combined effect of compaction and seasonal effect of rainfall on crop performance. Climate data was obtained from the Australian Bureau of Meteorology (BOM, http://www.bom.gov.au/silo/) weather station (41529) at Toowoomba via patched point data set (Jeffrey et al., 2001). A process modelling approach was chosen to quantify the likely impact of soil compaction on crop phenology, which was the method employed by Antille et al., (2016b); except that the SoilWat module was used to represent soil water processes instead of SWIM module (Huth et al., 2012) used in the study of Antille. Simulations involved testing of grain yield biomass and water use efficiency under the conditions representing of CTF and non-CTF traffic systems, respectively. This approach was applied to the simulations of both winter (wheat) and summer (sorghum) crops, respectively.

4.3.1. Soil properties and water balance

Measured soil data was used to represent drained upper limit (DUL) and saturated water content (SAT), and bulk density (BD) for CTF and non-CTF conditions to a depth of 300 mm, except for saturated hydraulic conductivity (K_{SAT}), which was measured to a depth of 150 mm. The BD data for 300-1800 mm depth and K_{SAT} for 150-1800 mm depth for CTF condition were derived and modified from measured data on a similar Red Ferrosol soil under available cropping (Dalgliesh and Foale, 1998;

Connolly et al., 2001). Pedotransfer functions were fitted for the CTF condition to estimate lower limit (LL) water content for all soil depths (0 to 1800 mm), and DUL and SAT water contents for the deeper depths (300 to 1800 mm) interval, using particle size analysis data obtained with the Pipet method (Gee and Bauder, 1986) as reported in **Chapter 3**. For non-CTF conditions, these data were obtained from measured field data (soil physical and hydraulic properties) and from the set of assumptions described by Antille et al., (2016b). Modelled runoff from rainfall is calculated using the USDA-Soil Conservation Service procedure known as the curve number technique. The procedure uses total precipitation from a design storm (IDF: intensity, duration, frequency) occurring on a given day to estimate runoff. A runoff curve number (that is runoff as a function of total daily rainfall), which describes runoff potential for bare-soil, was set at 73 units for CTF (Kodur et al., 2014); and was increased by 7 units for non-CTF conditions based on an earlier study by Owens et al., (2016). These relative differences between the assigned curves numbers were considered to be fair based on functioned relationships between traffic and rainfall (Li et al., 2009). Default soil evaporation parameters were set according to Kodur (2017). The default parameters are the ones that come as a default with the APSOIL database. Soil properties and input parameters used in the model are presented in **Table 4.1**.

Soil water content at saturation (SAT) was inferred from measured BD (to a depth of ≤ 300 mm) using **Eq. 4.1**, where 2.65 is particle density (g cm^{-3}) (Littleboy et al., 1996). Air-filled porosity of 0.05 v/v at the drained upper limit was assumed to be valid for swelling clays (Gardner, 1988).

$$SAT = 0.95\left(1.0 - \frac{BD}{2.65}\right) \qquad \mathbf{(4.1)}$$

Saturated hydraulic conductivity (K_{SAT}) of soil was measured for both CTF and non-CTF plots using the constant head method (Klute, 1965) as reported in **Chapter 3**. The outflow leachate was collected in beakers at the bottom of the column. The measurements of the leachate and timing of the duration required to obtain leachate enabled K_{SAT} to be determined. The K_{SAT} for a vertical soil core under constant head was determined with **Eq. 4.2** (Hillel 2004).

$$K_{SAT} = \frac{VL}{AHt} \quad \mathbf{(4.2)}$$

where: V: The volume of solution (mm^3), L: The length of the soil core (mm), A: The area of the soil core (mm^2), H: The water head from base of core to top of solution (mm), t: The time for V to flow through (h).

Drained upper limit (DUL) is the highest field-measured water content of a soil after it had been thoroughly wetted and allowed to drain until free drainage becomes negligible, and DUL is referred to as field capacity, which was measured based on Ratliff et al., (1983).

4.3.2. Crops simulation

Wheat (*Triticum aestivum* L. *c.v.* Sunmate) was sown every year on defined sowing rainfall (at least 20 mm over a 5-day period) between 15th May and 15th July. If the defined rainfall did not occur, the model was forced to sow a crop on 31st July so that cropping can occur every year. Wheat was sown at 100 plants per m^{-2} and received an N application rate of 110 kg N ha^{-1}, which corresponded with the optimum N application rate determined from urea within this work (**Section 5.3.2 – Table 5.1**). Nitrogen was applied 30 days after of sowing consistent with standard agronomic practice, which is based on the stage of the crop (Zadoks et al., 1974).

For sorghum, simulations were also conducted by specifying that the crop was sown every year on defined sowing rainfall (at least 25 mm over a 7-day period between Nov-Jan. If the defined rainfall did not occur, the model was forced to sow a crop on 31st January so that cropping can occur every year. Sorghum was sown at 14 plants per m^2, and received an N application rate of 140 kg N ha^{-1}, which corresponded with the optimum N application rate determine for urea within this work (**Section 5.3.2 – Table 5.3**). Nitrogen was applied 30 days after sowing, which was consistent with standard agronomic practice (Gerik et al., 2003). Initial moisture in the first year of study was 95% of maximum available water capacity and was obtained by prior running the model for 10 years.

Continued wheat and sorghum have been utilised as a templet to start the simulation using the APSIM framework. The assumption of continued wheat and sorghum was made to support farmer’s decision-making through simulating the long-term effects of soil compaction on agronomic performance.

In order to further represent the conditions of the current field study, the simulated grain yields for both CTF and non-CTF were calibrated, and validated against field data. For wheat, the difference in yield between CTF and non-CTF conditions under modelled conditions (13%) was similar to those observed under field (12%). For sorghum, the modelled yield was 10% higher than those measured and it was considered that this difference was reasonable. The estimation of water use efficiency (WUE) in high and low rainfall environments is complicated by unproductive water-use. Field trials undertaken with appropriately parameterised soil, climate, and crop growth and development are amenable to crop simulation modelling, using for example APSIM (Keating et al. 2003), to estimate yield and components of the water balance model (evapotranspiration, drainage and runoff) and thus calculate WUE. For the purposes of this work, simulated WUE defines as: the ratio of modelled grain yield (kg ha^{-1}) to total modelled rainfall (mm) that received during the corresponding crop season (Hochman et al., 2009).

Table 4.1. Soil properties used in the simulations† for CTF and non-CTF farming conditions for a Red Ferrosol soil at Toowoomba, Qld, Australia. The standard deviation (Std.) is shown for measured values as ± the mean value (n = 3), except when not shown (n = 1). Note: BD, bulk density; LL, lower limit, DUL, drained upper limit; SAT, saturation water content, and K_S, saturated hydraulic conductivity.

Depth (mm)	BD (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^{-1})
	Wheat	Sorghum	Wheat	Sorghum	Wheat	Sorghum	Wheat	Sorghum	Wheat	Sorghum	
CTF											
0-150	1.15±0.04	1.22±0.06	57±0.01	54±0.02	0.21	0.29	0.31± <0.01	0.30±0.02	54±0.01	51±0.02	1000±6.65
150-300	1.17±0.02	1.20±0.03	56±0.02	55±0.02	0.24	0.29	0.31± <0.01	0.34±0.01	53±0.02	52±0.02	500
300-600	1.20	1.20	55	55	0.22	0.35	0.36	0.36	52	52	100
600-900	1.20	1.20	55	55	0.24	0.38	0.35	0.37	52	52	50
900-1200	1.22	1.22	54	54	0.25	0.40	0.36	0.38	51	51	50
1200-1500	1.25	1.25	53	53	0.25	0.40	0.33	0.40	50	50	25
1500-1800	1.30	1.30	51	51	0.27	0.40	0.33	0.33	48	48	25
non-CTF											
0-150	1.34±0.04	1.37±0.05	49±0.01	49±0.01	0.22	0.30	0.26± <0.01	0.29±<0.01	47±0.01	47±0.01	50±0.08
150-300	1.27±0.03	1.27±0.04	52±0.01	52±0.01	0.25	0.30	0.28± <0.01	0.30±<0.01	49±0.01	49±0.01	25
300-600	1.30	1.30	51	51	0.24	0.36	0.37	0.37	48	48	10
600-900	1.28	1.28	52	52	0.25	0.39	0.35	0.35	49	49	25
900-1200	1.28	1.28	52	52	0.26	0.41	0.36	0.36	49	49	25
1200-1500	1.27	1.27	52	52	0.25	0.41	0.33	0.33	49	49	25
1500-1800	1.32	1.32	50	50	0.27	0.41	0.33	0.33	48	48	25

† † Data for BD, DUL, SAT and K_S data for 0 to 300 mm depth were directly measured in the field, data for 300-1800 mm depth were derived using pseudo-transfer function (DUL and LL from particle size analysis; K_{SAT} was based on adjustments using Red Ferrosol soil data by Connolly et al. (2001) and APSOIL database (Dalgliesh and Foale, 1998). Data for non-CTF conditions were adjusted based on field conditions, as explained (Antille et al., 2016b).

4.3.3. Climate

Simulations were conducted using SILO (Jeffrey et al., 2001) climate files for the experimental site, between 1955 and 2016. Long-term rainfall and temperature for the study area based on data for the simulation period (60-years) are shown in **Figure 4.2**. The climate of Darling Downs is temperate and sub-humid, with warm to hot, moist summers and cool, dry winters. The mean annual rainfall is 917 mm, two-thirds of this rain falling between October and March (BOM, 2016). Temperature records for the same period show that the average annual maximum and minimum temperatures are 22.6 ºC (range: 27.6 ºC in January to 16.2 ºC in July) and 11.5 ºC (range: 16.8 ºC in January to 5.6 ºC in July), respectively.

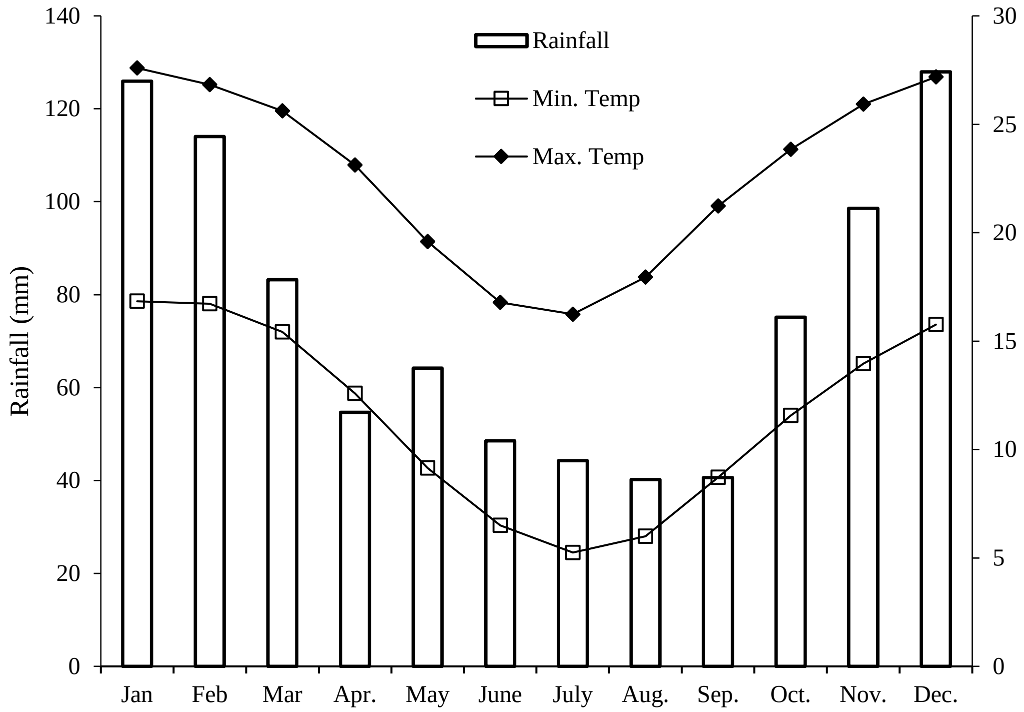


Figure 4.2. Average monthly maximum and minimum temperature and rainfall for long-term (1955-2016). Coordinates for Toowoomba (Queensland, Australia) 27°36'35.27" S, 151°55'50.62"E.

4.4. Results

4.4.1. Wheat

i. Simulation of crop performance

Simulated grain yield for 60 years of wheat production under compacted (non-CTF) and non-compacted (CTF) red Ferrosol soil are shown in **Figure 4.3**. The model showed that the difference between the two cropping systems was significant ($P<0.05$, $n = 60$), where the median yield was increased by (13%) within simulated CTF plots when compared to yields within other simulated systems. Similar reductions were recorded in the modelled aboveground biomass (13%) under non-CTF condition ($P<0.05$).

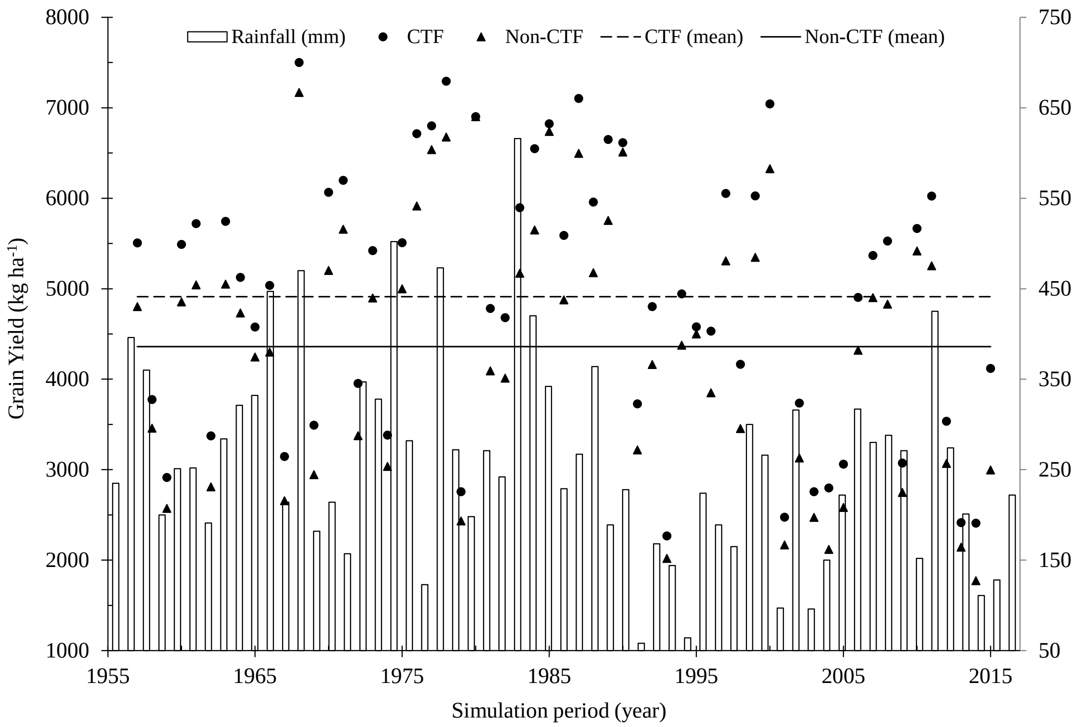
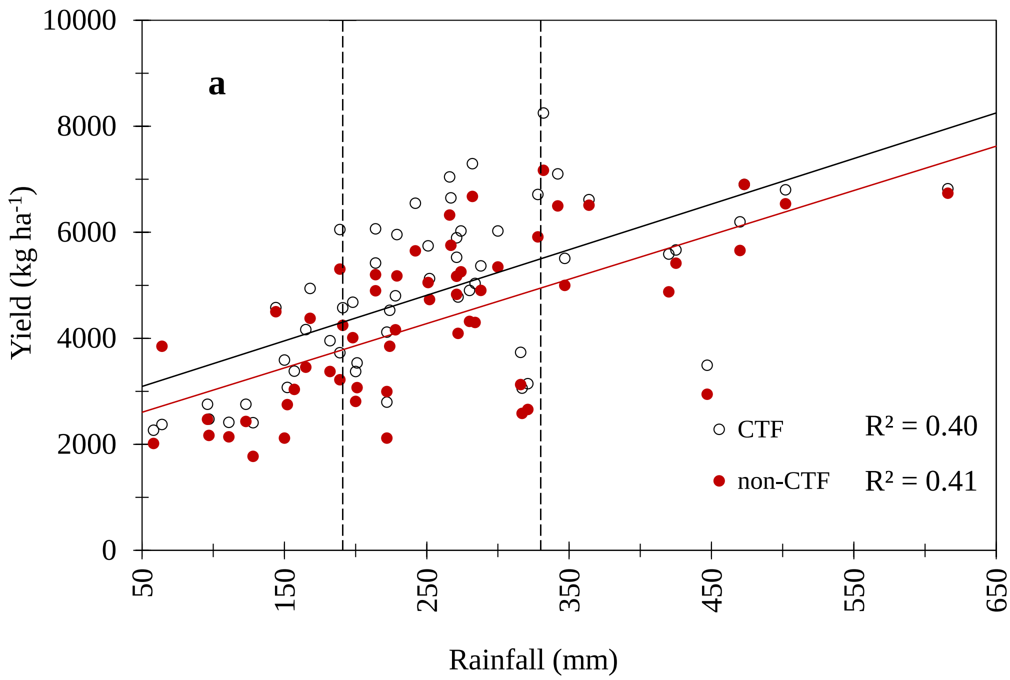
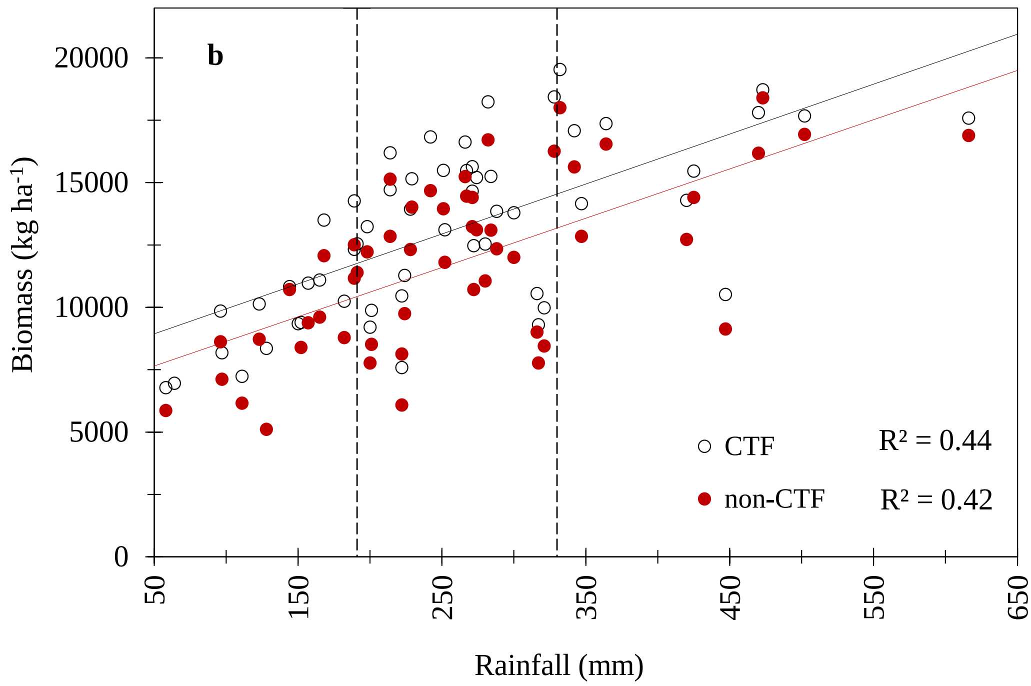


Figure 4.3. Annual modelled grain yield during simulation period (1955-2015) for continuous wheat under CTF and non-CTF cropping systems.

Modelled yield, biomass and water use efficiency (WUE) under rainfall variability for CTF and non-CTF conditions are shown in **Figure 4.4**. Soil compaction in non-CTF reduced in grain yield and biomass by 13%, and WUE by 15%, respectively. While these reductions were prominent across the rainfall conditions, the yield reduction was 12% greater during below average rainfall conditions (<30th percentile; average rainfall = 191 mm/season) than those of above average conditions (>70th percentile; average rain = 330 mm/season) (**Figure 4.4a**). The biomass reduction followed the same pattern, with soil compaction effects in drier years causing 11% greater biomass reduction than the wetter conditions (**Figure 4.4b**). Despite that differences in WUE between the two traffic systems were smaller above-average years, WUE were approximately 25% and 20% greater in CTF and non-CTF, respectively, in drier years compared with wetter years (**Figure 4.4c**).





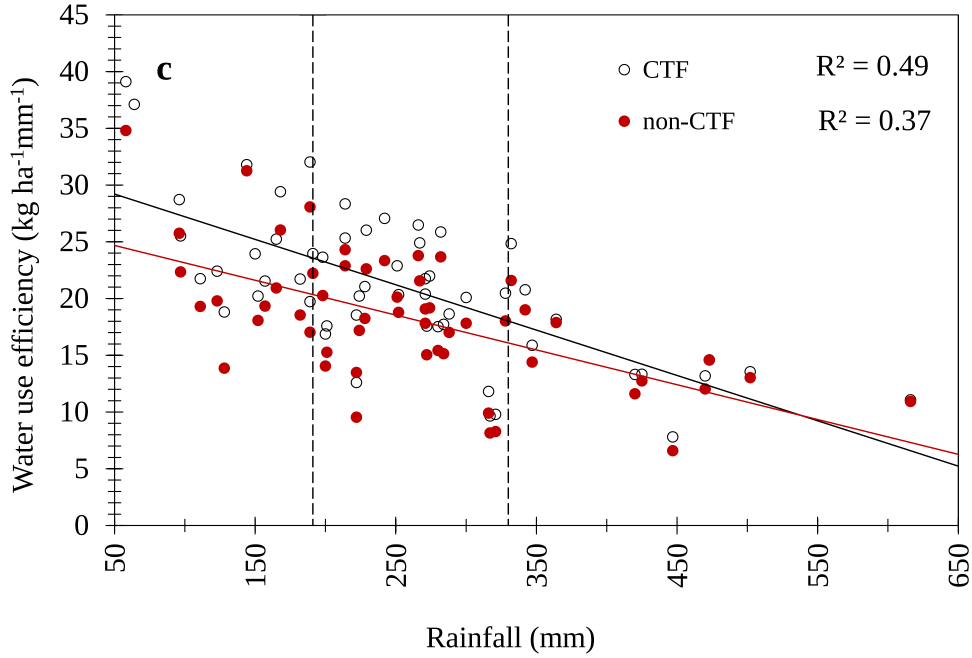
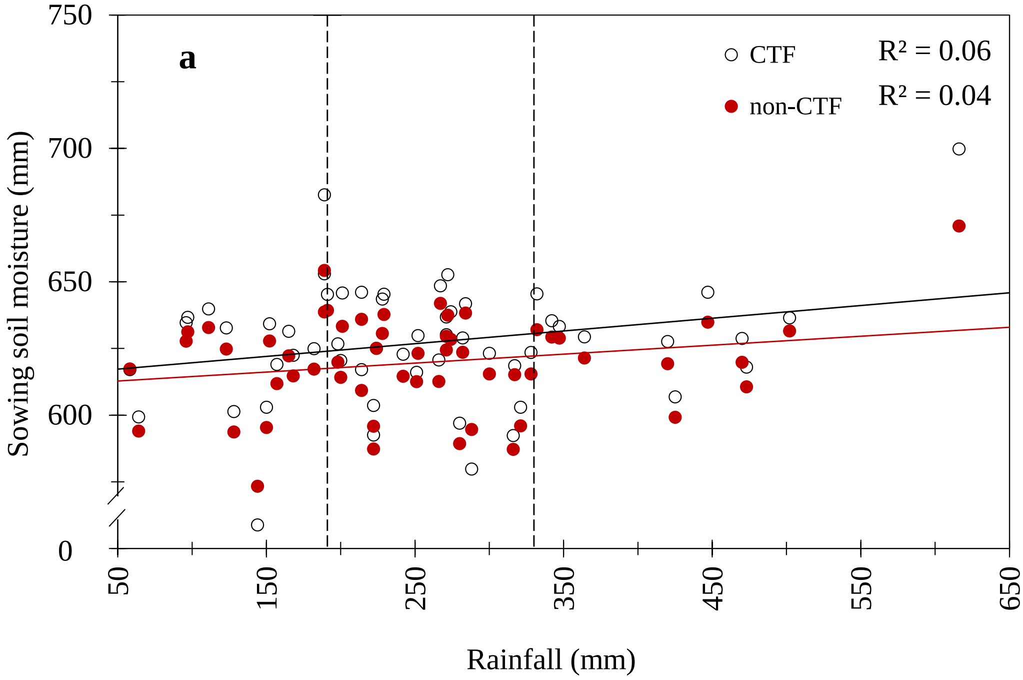


Figure 4.4. Yield (a), biomass (b) and WUE (c) for 56 years of simulated wheat-fallow cropping system on a Red Ferrosol soil at Toowoomba, Queensland for CTF (hollow circle), and non-CTF (red circle). Continuous lines show linear fit. Dotted vertical lines show30th (left) and 70th (right) *percentile rainfall*.

ii. Simulation of water balance

The negative effects associated with soil compaction on sowing soil moisture and runoff is shown in **Figure 4.5**. On average (56-year mean), soil compaction caused 7% reduction in sowing soil moisture, but 38% increase in runoff compared with that from CTF soil. In contrast to yield and biomass, sowing soil moisture and runoff were each increased with rainfall. That is, during above average rainfall conditions, soil compaction caused 6 mm (1%) greater reduction on sowing moisture (**Figure 4.5a**) and a 16 mm (45%) greater increase in the runoff (**Figure 4.5b**) than that did under CTF. There was no existed data for seasonal runoff, which therefore the simulation was conducted for annually.



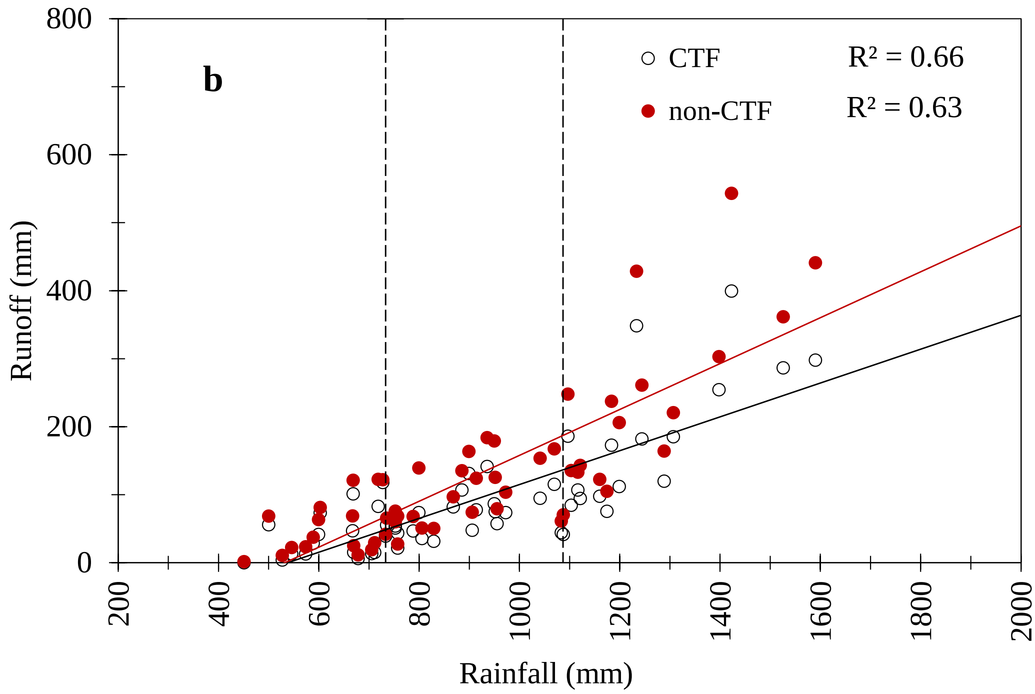


Figure 4.5. Sowing soil moisture (a) and runoff (b) for 56 years of simulated wheat-fallow cropping system on a Red Ferrosol at Toowoomba, Queensland for CTF (hollow circle) and non-CTF (black circle) systems. Continuous lines show linear fit. Dotted vertical line show 30th (left) and 70th (right) *percentile rainfall.*

4.4.2. Sorghum

i. Simulation of crop performance

Figure 4.6 shows the variations of grain yield during the wheat-harvesting season from 1955 to 2016 under two soil conditions (CTF, and non-CTF). Simulated grain yield and aboveground biomass were higher by up to 36% in CTF compared to non-CTF simulated system. The difference between the average of two traffic systems was significant ($P<0.05$) (ranged from 2619 to 3567 kg ha^{-1} for CTF, and from 660 to 3120 kg ha^{-1} for non-CTF conditions), respectively.

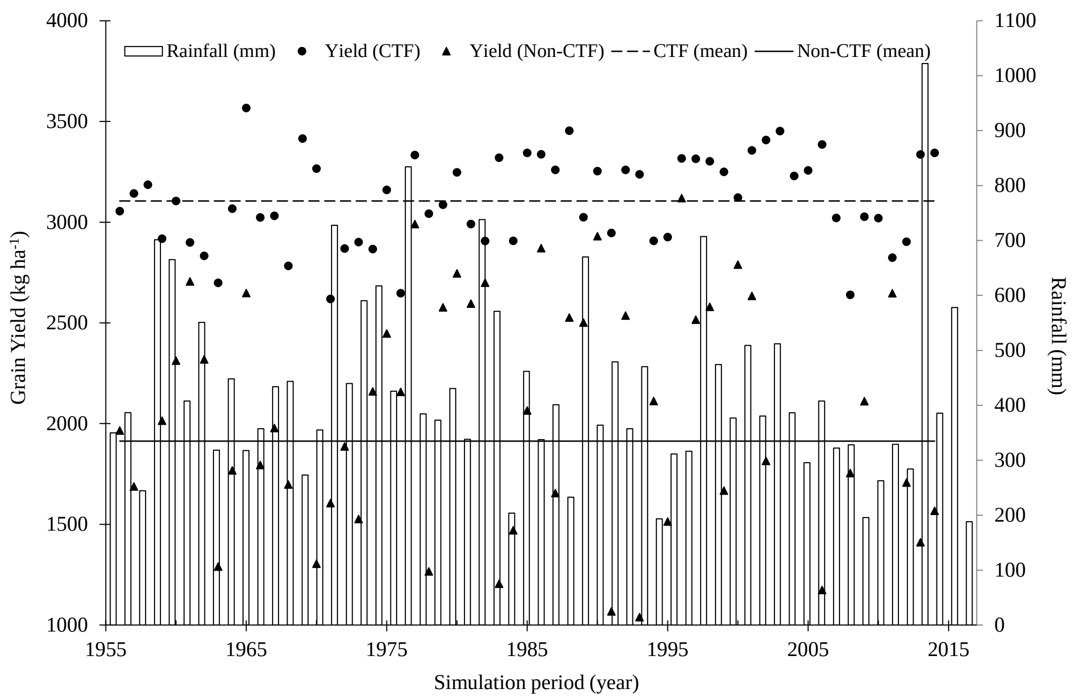


Figure 4.6. Annual modelled grain yield during simulation period (1955-2016) for continuous sorghum under CTF and non-CTF simulated conditions.

Modelled grain yield, biomass and water-use-efficiency (WUE) under different amount of rainfall for CTF and non-CTF conditions are shown in **Table 4.2**. Soil compaction in the non-CTF system had significant effects on these properties, with overall reductions of 32%, 38%, and 33%, respectively. While these reductions were significant across all rainfall conditions, which caused a 12% greater reduction in grain yield for below-average rainfall conditions (<30th percentile; mean rainfall = 386 mm/season) compared with the median rainfall conditions (>70th percentile; mean rainfall = 590 mm/season). Overall, the difference in WUE between CTF and non-CTF was up to 40% (≈8.40 for CTF, and 4.80 kg ha^{-1}mm^{-1} for non-CTF, respectively). **Table 4.2** shows the modelled long-term influence of rainfall on yield, biomass and WUE in both CTF and non-CTF.

Table 4.2. Grain yield, biomass and water use efficiency for 56 years of simulated sorghum-fallow cropping system on a Red Ferrosol for CTF and non-CTF. Below average (<30th percentile = 386 mm/season); average (390 mm/season); above average (>70th percentile=590 mm/season).

Rainfall category	Yield (kg ha^{-1})			WUE (kg ha^{-1} mm^{-1})			Biomass (kg ha^{-1})		
	CTF	non-CTF	Differences	CTF	non-CTF	Differences	CTF	non-CTF	Differences
Above average	2944	2259	685	5.51	4.11	1.40	8325	6400	1925
Average	3111	2093	1018	7.00	4.61	2.39	8347	5700	2647
Below average	3137	1676	1461	10.68	5.22	5.46	8379	4677	3702
Mean	**3064**	**2009**	**1055**	**7.73**	**4.65**	**3.08**	**8350**	**5592**	**2758**

ii. Simulated water balance

The negative effects associated with soil compaction on sowing soil moisture and runoff are shown in **Figure 4.7**. Soil compaction from non-CTF resulted in 1.5% reduction in sowing soil moisture, but 46% increase in runoff compared with the from the CTF soil. The negative effects of soil compaction on sowing moisture and runoff were increased with rainfall intensity. That is, for above average rainfall conditions, soil compaction caused a 2% reduction in sowing moisture (**Figure 4.7 a**) and a 45% increase in the runoff (**Figure 4.7 b**) than that under CTF.

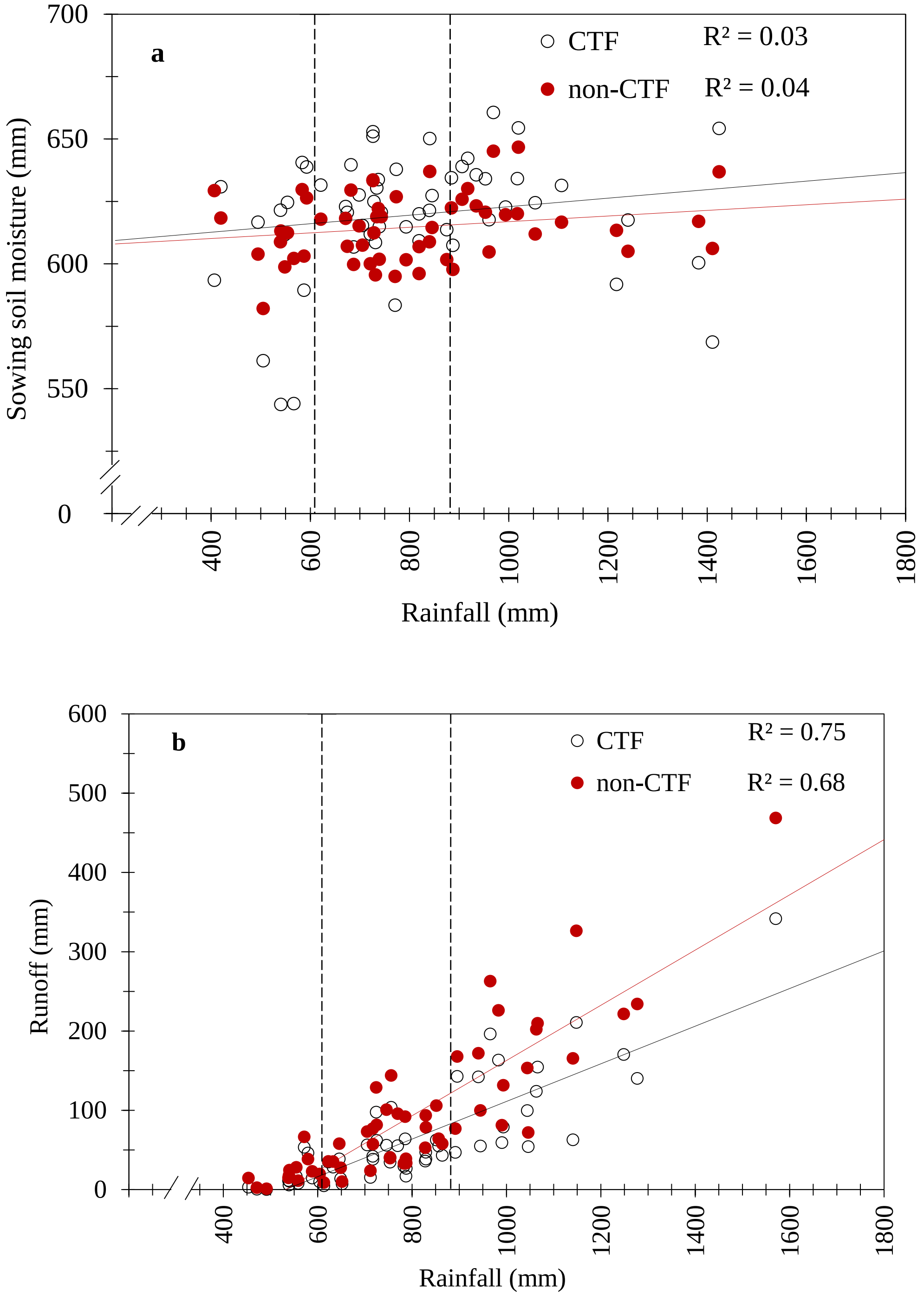


Figure 4.7. Soil moisture (a) and runoff (b) for 56 years of simulated sorghum-fallow cropping system on a Red Ferrosol at Toowoomba, Queensland for controlled traffic farming (CTF, black circle) and non-controlled (non-CTF, red circle) systems. Continuous lines show linear fit. Dotted vertical lines show 30th (left) and 70th (right) percentile rainfall.

4.5. Discussion

The model was validated/calibrated using the current field results and hence the modelled results closely followed the current field study. The conditions of the current field studies differed from many other field experiments in terms of experimental conditions - including the differences in average annual rainfall (about 780 mm vs 400 mm per year for the other studies in the region), the use of clay red soil vs clay black and grey, and crop variety. Thus, differences in grain yield data between two distinct crop types (wheat and sorghum) were regarded as reasonable between this study and the other studies conducted in the region.

The APSIM wheat and sorghum modules have also been previously validated across various soil (Hammer et al., 1995; Moore et al., 1997; Probert et al., 1998b; Dolling et al., 2005; Peak et al., 2008; Huth et al., 2014; (Table 2.5).Climate and management conditions; and also that the model is validated using 1-year field data from this specific study.

The modelling results suggested that soil compaction is likely to reduce crop yield and biomass and WUE on a longer-term irrespective of climate conditions, similar to those found under short-term field study. The negative effects associated with soil compaction were more significant in below-average rainfall years. Soil compaction affects crop growth and development through reduced moisture storage, and roots uptake ability (Barraclough and Weir, 1988). The nutrients can be taken by plant mainly through mass flow mechanism, which occurs when nutrients are transported in solution by means of a water flow from the soil matrix to the roots (Divito et al., 2011) and it is therefore driven by plant transpiration (Kirkby et al., 2009). Hence, the amount of a particular nutrient taken up by the plant is dependent on the volume of water entering the roots and the concentration of the nutrient in the solution (Divito et al., 2011). Therefore, improved WUE in a CTF system resulted in higher NUE and grain yield as reviewed in the field studies **(Chapter 3**), and reviewed in (**Chapter 2).**

The simulated yield reduction for soil compaction from this study was smaller than those found for similar studies on wheat grown in subtropical environments. For example, studies by Radford et al. (2007) and Antille et al. (2016b) found a yield reduction from soil compaction of 43% and 53%, respectively. These discrepancies can be attributed to the soil type where wheat and sorghum crops in this study were grown on Red Ferrosol which has a higher drainage porosity (SAT-DUL; Table 2), than the Vertosols reported in those studies. A higher drainable porosity allowed greater infiltration even under compaction, leading to greater water loss in the form of drainage, which was otherwise used by crops for growth and development.

Soil compaction reduces the soil moisture at sowing, which is a key determinant of crop performance (Júnnyor et al., 2015). Successful dryland crop production, especially in arid and semi-arid regions, relies heavily on moisture stored at the time of sowing (Freebairn et al., 2009). Therefore, the modelled differences in this water available at sowing will inevitably impact the establishment of the following crop and the decision-making associated with sowing (Kodur et al., 2017). Similarly, soil compaction will have negative impacts on runoff, which is due to reduced soil infiltration causing surface ponding followed by horizontal movement of water as runoff (Acuña et al., 2015; Hammer et al., 2010). Drier conditions lead to greater reduction in fertiliser use efficiency, yield and biomass which is due to the higher water stress (Probert et al., 1995). Whereas, during high rainfall conditions, soil moisture will be less limiting to reduce crop yield and biomass under non-CTF and CTF, although runoff will be considerably higher.

A higher yield reduction for wheat in the simulated conditions of non-CTF system compared with CTF was as expected because it was grown under winter conditions which received lesser rainfall than the summer grown sorghum. During drier conditions, moisture is more limiting for crop performance. Therefore, greater yields and WUE reduction are as expected from soil compaction, as it limits the moisture supply for crop performance. Whereas, a higher runoff during cropping period under wetter conditions, but relatively lower reduction in the associated yields under both CTF and non-CTF suggests that increased runoff loss had little effect in reducing biomass or yield. This is because moisture was a less limiting factor under higher rainfall conditions and any reduction in infiltration or increases to runoff from soil compaction may have an insignificant effect on the stored soil water. This effect is especially prominent for Red Ferrosol soil type; as associated higher drainable porosity will still allow enough water to pass through the root zone, filling the root zone with water. Similar conclusions were drawn elsewhere for Red Ferrosol (e.g., Bell et al. 1997), where improvements in infiltration characteristics were found to have had little effect on increasing stored soil water due to infiltration amount frequently exceeding the soil's water holding. The long-term estimations of WUE compare with rainfall use efficiency (RUE) observed in the winter season of 2014/2015 and summer season of 2015/2016 for CTF and non-CTF treatments were showed in **Table 4.3**.

Table 4.3. Long-term modelled WUE (1955-2016) and short-term RUE (2014-2016), respectively, for the two crops and both traffic treatments.

	CTF			**Non-CTF**		
	WUE	RUE	Difference	WUE	RUE	Difference
	(Kg ha^{-1} mm^{-1})			(Kg ha^{-1} mm^{-1})		
Wheat	20.90	12.77	8.13	17.80	11.25	6.55
Sorghum	8.40	6.77	1.63	4.80	3.68	1.12

While this study captured the seasonal differences in crop performance and water balance under soil compaction, further work may be required to model the rainfall-runoff relationships representative of CTF and non-CTF, respectively. While this has been done experimentally at the field scale (e.g., Tullberg et al., 2001), the modelling approach developed within this study would enable conduct-scale modelling incorporating changes in arable land use such as increased area under CTF coupled with no- or zero-tillage. Although the model can account changes in conductive properties due to soil compaction (e.g. through K_{SAT} values), these effects were poorly impacted the crop productivity on the studied Red Ferrosol soil especially due to associated higher drainable porosity. Thus, the accuracy of the modelled effects of soil compaction on water balance and crop productivity relied mainly on the assumptions on runoff curve number. Field studies are needed to derive improved runoff curve number according to the extent of soil compaction (including surface sealing properties) and associated changes in soil water balance. All modelled results are shown in **Appendices (B.1- B.4)**.

4.6. Conclusions

A novel modelling approach using APSIM has been developed to quantify likely reductions in grain yield, yield components and WUE due to long-term effects of soil compaction that are typical of non-CTF systems. This modelling work has been developed for Red Ferrosols but the principles are readily applicable to other soil types, and therefore compliments earlier investigations in this scop (Antille et al., 2016b). The main conclusions derived from this Chapter are:

- It has been found that in south-eastern Queensland, wheat and sorghum yields and WUE were positively correlated to the soil conditions offered by CTF (soil mechanical and hydraulic properties), and the growing season rainfall, while being negatively correlated to the soil conditions typically found in non-CTF systems.
- CTF has potentially reduced runoff by comparison with non-CTF. water saved in runoff is used for timely crop establishment, yield and cropping frequency which together have a significant impact on form profitability.
- Predicted reductions in grain yield and biomass during drier years were significantly higher compared to average rainfall conditions, by up to 12% for both wheat and sorghum.
- The model predicted runoff to be significant (non-CTF was 38% higher in wheat and 46% in sorghum compared with CTF) and therefore it appears that this could be the main factor influencing crop yield. However, small differences in soil moisture at sowing would have a significant effects on timely crop establishment and plant population, and will determine the frequency of successful crops in dryland relation and hence the profitability of arable cropping.

- Based on the data of water holding capacity of both simulated traffic systems, water use efficiency was higher by up to 15% for wheat and 40% for sorghum in CTF compared with non-CTF system as a reducing runoff and soil strength.

5. ECONOMIC ANALYSIS

5.1. Introduction

In this chapter, the assessment conducted for the two traffic systems in the field studies will be completed by integrating the agronomic analysis with an economic analysis. The economic performance is affected by the crop response to applied nutrients, the fertiliser price, and the relationship between the price of grain and price of fertilisers. The analysis presented in this chapter aims to identify the potential economic benefits of using different nitrogen fertiliser formulations (**Chapter 3**) when they are applied to wheat or sorghum crops grown under controlled and non-controlled traffic.

Ultimately, the success in the adoption of CTF is measured by the economic return that this technology can provide to farmers, relative to that achieved with a conventional, non-controlled traffic system. This could come from increased crop yield or reduced input costs (James, 2000) including the costs associated with the use of fertilisers. James (2000) discussed the question of whether variable rate application of nitrogen fertiliser was economically advantageous compared with uniform application strategies. A similar question can thus be formulated in the context of the present work and it is whether the use of CTF in grain cropping production is more profitable than the use of other mechanisation systems (non-CTF) due to improved efficiency of fertiliser use.

This chapter focuses on the economic analysis of crop responses to applied fertiliser (**Chapter 3**), as affected by the two levels of compaction representing the soil compaction of CTF and non-CTF, respectively. For this, the optimum economic N application rates and corresponding grain yields will be determined for which crop gross margins will be derived. The economic analysis of the crop responses to applied nitrogen fertiliser under wheeled and non-wheeled conditions was based on the results obtained for short-term (field studies) as well as long-term that reported in Chapter 3 and Chapter 4, respectively. The scenarios were based on the approach reported earlier (**section 2.7.1**) by James and Godwin (2003). Therefore, the specific objectives of this chapter are:

- To determine the most economic rate of nitrogen (MERN) and their corresponding crop yield (Y_{MERN}) based on the approach reported in the earlier study by James and Godwin (2003),
- To determine the crop gross margins, and the relative differences between the two traffic treatments using the MERN and Y_{MERN} analyses previously concluded,
- To determine the impact of fertiliser-N formulation on crop gross margins for the two traffic treatments.
- To conduct sensitivity analyses to determine changes in the crop gross margins as a result of changes in the price of nitrogen fertiliser and fluctuations below and above the mean price of the grain as well as the yield of the crop, and
- To provide recommendations that assist the choice of N fertiliser with a view to maximising the economic return.

5.2. Grain and nitrogen prices

5.2.1. Overview

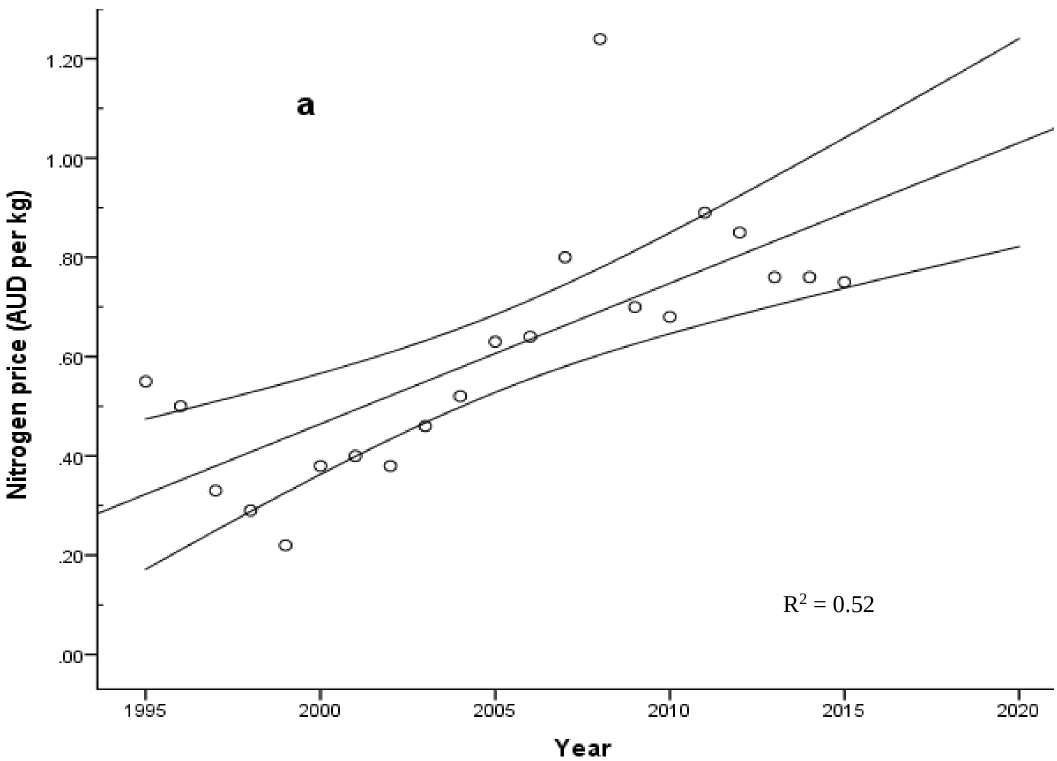
The agricultural sector is just like any other sectors and can be affected by the global economic growth and financial situations. From the beginning of the last decade, the world economy has experienced a financial crisis in 2008 followed by a slump in growth with intermittent recovery and most recently a broader strengthening, which was continued during 2014-2015. During the same period, the food prices have increased, reversing the long-run trend of decline in relative food prices over the past decades. Since the recession of 2007-2008, the global economy and in particular the food price volatility has been front and centre in the international development conversation. The crisis saw a dramatic rise in the international price of grains and other important commodities, while the years immediately afterwards saw increasing international grain price fluctuations despite the global economy has recovered and grown following the 0.6% decline observed in 2009 (Heffer and Prud'homme, 2010). For the purpose of this project, the nitrogen fertiliser prices, and the prices of wheat and sorghum are therefore viewed from the perspective of the world economic growth situation.

5.2.2. Fertiliser demand and prices

In order to increase the crop productivity, three basic fertilisers are usually applied to the Australian soils. Phosphate, nitrogen and potassium are the three basic fertiliser materials that can be coated, processed and blended with other products (e.g., copper, calcium, zinc and manganese) to produce another fertiliser. Nitrogen fertilisers are the most common fertiliser component used in Australia (ACCC, 2008).

Globally, the demand for nitrogen fertiliser has increased a rate of 1.5% since 2013, and it will remain steady (FAO, 2018). Therefore, nitrogen fertiliser prices are expected to be sustained in the future, particularly if the price of natural gas (energy) are also sustained.

An analysis of N fertiliser was conducted to two price datasets (**Figure 5.1**). For this, a fertiliser N dataset from 1995 to 2017 was considered. Two analyses were conducted which considered the full dataset, but excluding fertiliser prices for 2008. However, it may be argued that the use of the full price dataset (1995-2017) would provide a better indication of the natural volatility of fertiliser (and energy) prices. Therefore, in this chapter, in order to account for this volatility, economic analyses would be conducted considering not only the projected price of the fertiliser using the full price dataset available (1995-2017) but also the upper 95% confidence interval of the regression analysis.



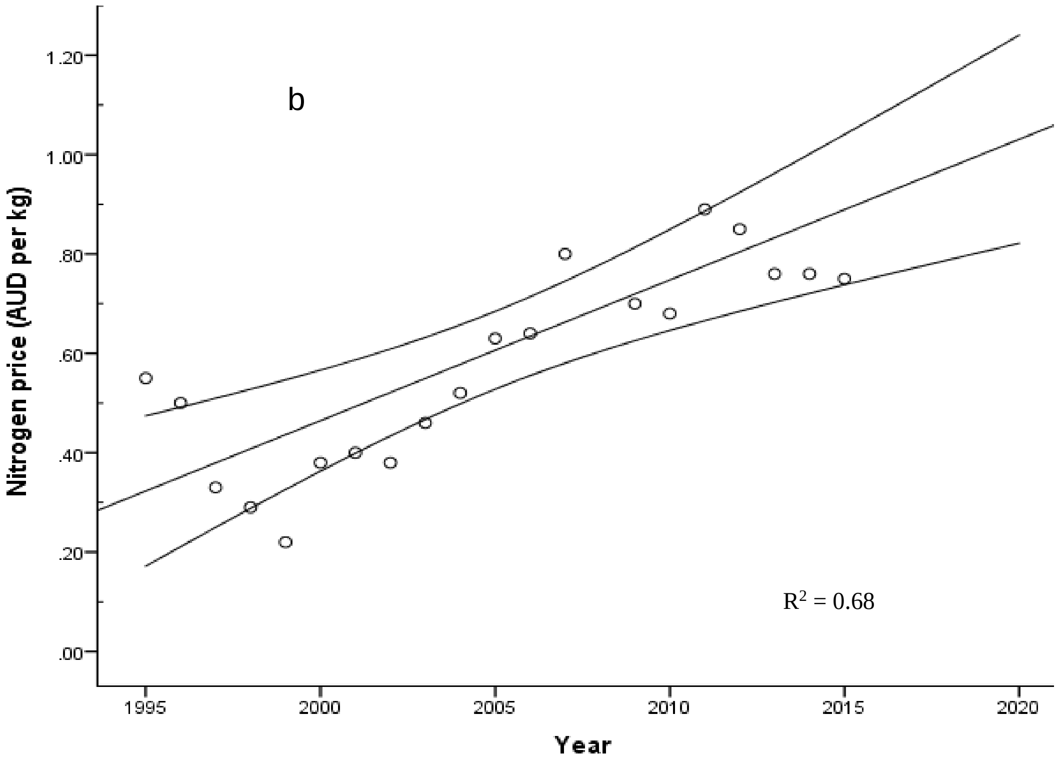


Figure 5.1. Price of urea-N for the period 1995-2017 in Australia (source: Index Mundi, 2017) and predicted price to 2020. (a) Including price corresponding to 2008, and in (b) the price of this particular year was removed. The two curves on both sides of the fitted line represent its 95% confidence interval.

The fertiliser prices reviewed in **Figure 5.1** also shows that the linear relationships between the nitrogen price and the time are acceptable fits as indicated by the R^2, particularly when the data corresponding to 2008 are removed from the dataset. Exponential relationships between the fertiliser price and the time are also possible but they were, however, not applied. Overall, the linear models fitted are considered to be simpler and provide a more cautious approach to describing these relationships. The regression analysis indicated that, assuming that the price of nitrogen fertilisers is expected to increase by approximately 25%. Therefore, the range of N fertiliser price used in the sensitivity analysis was (±25% of the constant price) (will be described later in the section of the sensitivity analysis).

5.2.3. Grain prices

The areas planted to sorghum in Australia is approximately 500,000 ha, which produces about 2.5% of the global production of sorghum and account for more than 5% of global exports. Overall, the Australian wheat and sorghum prices followed the global grain prices with mean values of wheat AUD 248 per ton, and AUD 193 per ton for sorghum as reported by (Index Mundi, 2017). The data shown in **Figures 5.2 and 5.3**, retrieved from Index Mundi for the period 1995 to 2016 shows the annual changes in budgeted values for wheat and sorghum and do not include the full range of price changes that might have occurred in the price series during that period. The use of this data is justified since the gross margins analyses in **Section 5.3** were undertaken using the grain prices for the harvested seasons.

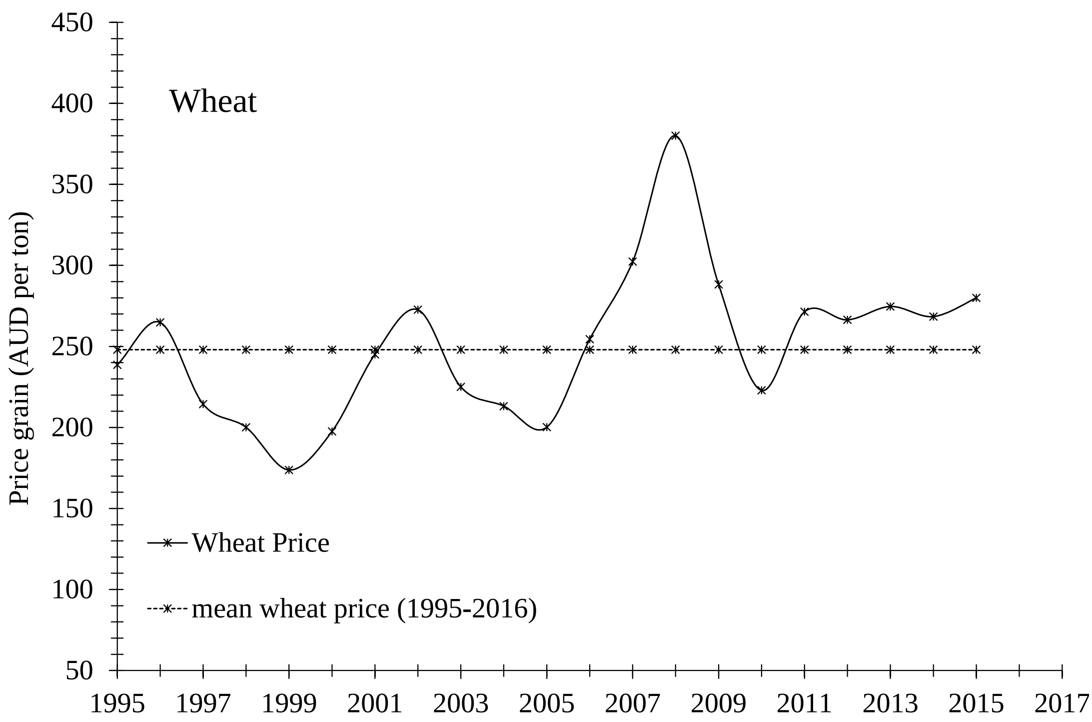


Figure 5.2. Mean annual realised (producer) price of wheat in Australia and mean price for the period 1995-2016 (source: Index Mundi, 2017).

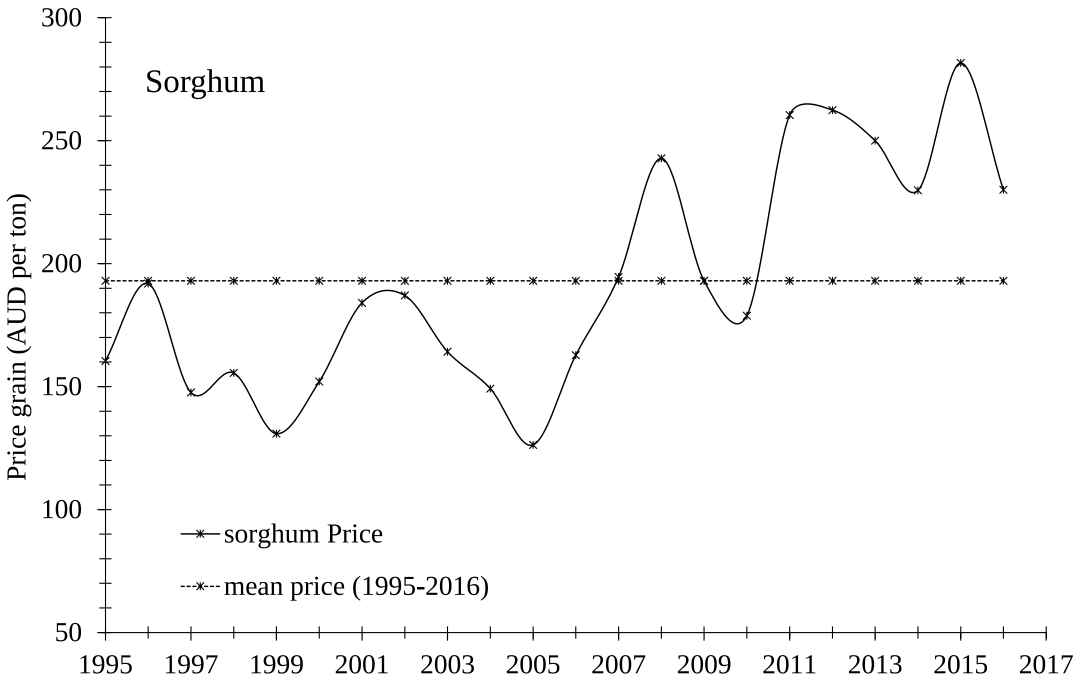


Figure 5.3. Mean annual realised (producer) price of sorghum in Australia and mean price for the period 1995-2016 (source: Index Mundi, 2017).

The increase in the price of wheat in Australia observed in the last 10 years, responded, in part to the reduction in wheat as reported in **Chapter 2** (ABARES, 2017). Fertiliser prices in Australia remained 40% above the prices recorded in the period prior to the global financial crisis. However, the price of wheat has increased by around 12% after the economic crisis. The production of wheat in Australia was recorded 11.3% above the average for the harvested season of 2016, while the price of the grain was 20% below the average. However, the overall decline in the price of sorghum prior to the recession was, to a certain extent, accompanied by a decrease in the price of nitrogen fertilisers since supply rapidly surpassed demand (**Figure 5.2)**.

5.3. Profitability analysis

5.3.1. Methodology

i. Most economic rate of nitrogen (MERN)

The gross margin (GM) is defined as the difference between gross income (GI) and total variable costs (TVC) includes the cost of seeds, fertilisers, agrochemicals, and casual contract work **Eq. (5.2)**. Gross income and total variable costs were calculated using **Eq. (5.2)** and **Eq. (5.3)**. To make the comparisons between the results that were obtained from the three fertiliser types easier, the yield of crop corresponding to the most economic rate of nitrogen (MERN) was used as the basis to determine the gross income. This was possible since the response curves for each fertiliser type were available, which allowed the MERN and its corresponding yield of crop (Y_{MERN}) to be calculated for a range of price ratios; that is the price of nitrogen relative to the price of crop, as shown in **Eq. (5.11)**.

$$GM\ (\text{AUD}\ ha^{-1}) = GI(\text{AUD}\ ha^{-1}) - TVC\ (\text{AUD}\ ha^{-1}) \qquad (\mathbf{5.1})$$

where: GM is gross margin of the crop, GI is gross income and TVC is total variable costs.

Yield-to-nitrogen response relationships were examined by applying nonlinear regression analyses, and by fitting quadratic functions to the data (Abraham and Rao, 1965) as will be explained later in this chapter. The approach used in this work is from studies (e.g., Kachanoski, 2009; Antille et al., 2017) dealing with cereal crop responses to applied N fertiliser, and assumes a quadratic-plateau relationship. This analysis uses the optimum N application rate (MERN) as the N_{RATE} required to calculate the cost of nitrogen. This is used to estimate the fertiliser component of the variable costs and also to derive the corresponding grain yield from the yield-to-nitrogen response curve.

Therefore, GM reflects the gross profitability of the crop when the fertiliser N input is optimised.

$$TVC\ (\text{AUD}\ ha^{-1}) = \sum Variable\ costs\ (S, F, A, C) \qquad \mathbf{(5.2)}$$

where:

- S: cost of seeds;
- F: cost of fertilisers;
- A: cost of agrochemicals; i.e. herbicides, fungicides, insecticides, growth regulators;
- C: cost of casual and contract work.

$$GI\ (\text{AUD}\ ha^{-1}) = Y_{MERN}(kg\ ha^{-1}) \times P_C\ (\text{AUD}\ kg^{-1}) \qquad \mathbf{(5.3)}$$

where: Y_{MERN}: modified crop yield corresponding to MERN which was determined based on the **Equations [5.4, 5.5, 5.6]** (Kroulík et al., 2011) after considering the area affected by traffic, and P_C is price of crop (kg ha^{-1}).

The components of the total costs were categorised to variable and constant costs. Seed, operations, and agro-chemical costs were identical costs in both traffic treatments. Seed cost included costs of seed and seed treatments, and the operations cost included the costs of fuel, repairs and maintenance of agricultural machinery. In practice there are significant differences in machinery fuel consumption, repairs and maintenance between the two traffic systems (e.g., Tullberg, 2000; Luhaib et al., 2017), mainly because differences in energy requirements (tillage, fuel, rolling resistance). However, in my study, the main focus was to understand the effects of improved fertiliser use efficiency on gross margins (GM). Therefore, the analysis was based on relative effect of fertiliser cost on GM for the two traffic systems investigated in this study. A simplification was made by assuming that variable costs were identical in both traffic treatments; except for the fertiliser costs, which were dependent on the MERN. Further studies should be conducted to expand the findings from these experiments by accounting for differences in machinery and energy-related costs, which were not the focus of this study. Similarly, differences in fertiliser cost within traffic treatments are depending on fertiliser type. In well-design CTF systems in Australia, the area subject to traffic typically occupies 15% (or less) of the cultivated field area, particularly when permanent zero-tillage is practised (Tullberg, 2007). By contrast, where CTF is not practised, this area is often greater than 65% when shallow tillage is practised and 45% when zero-tillage is practised, and it can be as high as 85% in conventional tillage systems that require primary tillage operations prior to crop establishment (Kroulík et al., 2009).

In Australia, both tillage systems (shallow tillage, zero-tillage) are used. Therefore GM calculations were adjusted to reflect the effect on yield of the relative areas affected and not affected by traffic compaction in typical CTF and non-CTF systems, respectively. For shallow tillage (ST), it was assumed that 65% and 35% of the cultivated field area in the non-CTF system was and were not subject to traffic compaction, respectively. When zero-tillage (ZT) is practised, it was assumed that 45% and 55% of the cultivated area in the non-CTF system was and was not subject to traffic compaction, respectively. For the CTF + zero-tillage system, these relative areas were 15% and 85%, respectively. Hence, the corresponding GI for each traffic system was derived by adjusting Y_{MERN} in **Eq. (5.4)**, **Eq. (5.5)** and **Eq. (5.6)** by these relative percentages, respectively. This was considered to be a fair assumption based on earlier studies (e.g., Galambošová et al., 2017).

$$Y_{MERN}(non - CTF + ST) = [(Y_{MERN}(CTF) \times 0.35) + (Y_{MERN}(non - CTF) \times 0.65)] \quad (\mathbf{5.4})$$

$$Y_{MERN}(non - CTF + ZT) = [(Y_{MERN}(CTF) \times 0.55) + (Y_{MERN}(non - CTF) \times 0.45)] \quad (\mathbf{5.5})$$

$$Y_{MERN}(CTF + ZT) = [(Y_{MERN}(CTF) \times 0.85) + (Y_{MERN}(non - CTF) \times 0.15)] \quad (\mathbf{5.6})$$

where: Y_{MERN} is crop yield correspondent to MERN (kg ha^{-1}); CTF and non-CTF are controlled and non-controlled traffic farming systems, 0.65 and 0.35 are the relative areas that were and were not subject to traffic compaction, respectively, under non-CTF system when 'shallow tillage' is practised; 0.45 and 0.55 are the relative areas that were and was not subject to traffic compaction, respectively, under non-CTF system when 'zero tillage' is practised; 0.15 and 0.85 are the relative areas that were and were not subject to traffic compaction, respectively, under CTF system. This assumption is considered to be an appropriate as ZT is practised by most growers who have converted to CTF system (Tullberg, 2007), with some exceptions (e.g., Dang et al., 2017). It was also assumed that traffic lanes of CTF system are planted.

ii. Gross margins (GM)

The gross margin that is derived from the equations above is not equivalent to profit unless it takes into consideration other costs such as rent, labour, machinery and general overheads (Nix, 2010). The use of a farmer's own machines and labour is considered to be a constant cost whereas the employment of contractors is usually regarded as a variable cost (Nix, 2010). The main costs included were the cost of fuel (AUD12.39 ha^{-1}), repairs and maintenance (AUD14.66 ha^{-1}), and agro-chemicals including pre-emergent (AUD55.13 ha^{-1}), post-emergent by (AUD9.03 ha^{-1}), and fungicides by (AUD12.90 ha^{-1}).

The calculation of gross margins using this method implies that all other variable costs that were related to the fertilisation are identical, with the exception of the costs of fertiliser itself. However, this is not exactly true since the cost of spreading varies in relation to the concentration of nitrogen in the product and the nitrogen rate applied which need to be accounted for as they are directly associated with the practice of fertilisation. Therefore, the fertilisers costs (C_F) can be defined to include the cost of fertiliser spreading in addition to the unit price of nitrogen and the rate used as shown in **Equation (5.7):**

$$C_F\ (\text{AUD}\ ha^{-1}) = C_S(\text{AUD}\ ha^{-1}) + [P_N(\text{AUD}\ ha^{-1}) \times MERN\ (\text{AUD}\ ha^{-1})] \quad \mathbf{(5.7)}$$

where: C_S is cost of fertiliser spreading, P_N is price of nitrogen, and MERN is the most economic application rate of nitrogen.

The quadratic functions applied to the yield to nitrogen responses **(Tables 5.1, 5.3)**, allow MERN to be calculated (James and Godwin, 2003). The shape of the response curve reflects the combined effect of soil compaction and fertiliser formulation on crop yield, and therefore, on profit margins.

Given:

$$y = a + bx - cx^2 \quad \mathbf{(5.8)}$$

where: y is grain yield (kg ha^{-1}), x is nitrogen application rate (kg ha^{-1}), and a, b, c, are regression coefficients.

Thus,

$$\frac{dy}{dx} = b - 2cx' = R_P \quad \mathbf{(5.9)}$$

where: x′ (N_{MAX}) is maximum rate of nitrogen application (kg ha^{-1}), and R_P is price ratio.

Then,

$$N_{MAX} = \frac{b}{2c} \quad \mathbf{(5.10)}$$

And,

$$R_P = \frac{P_N}{P_C} \quad \mathbf{(5.11)}$$

And,

$$\text{MERN} = \frac{b - R_P}{2c} \quad \mathbf{(5.12)}$$

where: P_N is the price of nitrogen (AUD kg^{-1}), and P_C is price of crop (AUD kg^{-1}).

The R_P is defined as the breakeven ratio and indicates the extra return of the produce that just covers the extra unit of nitrogen added. The most economic grain yield (Y_{MERN}) and the maximum grain yield (Y_{MAX}) are calculated by replacing the actual value of MERN and N_{MAX}, respectively, by (x) on the quadratic function **(Equation 5.8)** and by subsequently solving the equation. The results shown in **Table 5.1** and **Table 5.3** are represented the MERN and the economic yield which correspond to the MERN for wheat and sorghum crops respectively. The calculations of these values were derived from the quadratic equations obtained for crop responses to applied fertiliser nitrogen, and the corresponding price ratio for the year of harvest. These results were used to calculate gross margins for the two crops tested in the field studies.

In order to estimate the GM of wheat and sorghum in the controlled and non-controlled traffic systems, it may be necessary to add the costs of seed, operations and agrochemical as well as the fertilisers costs although these costs are identical (except the cost of fertilisers) under the two traffic systems. Therefore, the **Equation 5.1** was used to calculate the GM. The only scenario that has been used to estimate the GM was considered using the farmer's equipment and labour.

For wheat, the cost of spreading fertilisers was considered to be identical regardless the fertiliser type and material (granular or liquid). The costs of fertiliser spreading (AUD8.5 ha^{-1}) and the cost of 40 kg ha^{-1} of Granulock Starter fertiliser (AUD32.4 ha^{-1}) were included in the overall fertiliser costs that were applied to wheat crop and reported in **Table 5.5**. The cost of seed included seed treatment and these costs were identical for both traffic systems by AUD17.4 ha^{-1} for seed and AUD2.94 ha^{-1} for seed treatment considering the sowing rate was 60 kg ha^{-1} as reported in **(Section 3.2.2)**.

In the following section**,** a sensitivity analysis was conducted to investigate changes in crop gross margins as a result of changes in the price of nitrogen and the grain, respectively. This provided an indication of the relative effect that such changes had on gross margin, depending upon the fertiliser type used.

iii. Sensitivity analyses

The two main components influencing gross margin are the price of the nitrogen (P_N), the grain (P_C), and also the relationship between the two, which is reflected in the price ratio (R_P). The analyses were conducted assuming P_C at constant price (the mean price of wheat and sorghum, respectively, for the period 1995-2016), and also for P_C ±40 of the mean grain prices. The mean price of wheat and sorghum between 1995 and 2016 were AUD0.25 kg^{-1} and AUD0.19 kg^{-1}, respectively. The minimum and maximum prices of wheat recorded for the period were AUD0.17 and 0.38 kg^{-1} in 1999 and 2008, respectively, and for sorghum AUD0.13 and 0.28 kg^{-1} in 2005 and 2015, respectively. The average prices of N fertiliser were AUD0.63 kg^{-1} for urea ammonium nitrate (UAN), AUD0.82 kg^{-1} for ENTEC urea, and AUD0.61 kg^{-1} for urea, respectively. The price of N for all fertiliser materials fluctuated ±25, approximately, over the period 1995-2016.

The results of fertiliser and grain prices analyses (**Section 5.2**) suggested that, if recent price trends continue, then prices of fertiliser and grain would increase by 25% and decrease by up to 40%, respectively, by 2020 relative to 2015. Therefore, the sensitivity analyses were created and developed based on these assumptions of changes in price and price ratio.

5.4. Results and discussion

1.5.1. Most Economic rate of nitrogen (MERN)

For wheat, **Table 5.1** shows the most economic rate of nitrogen (MERN) and corresponding grain yield (Y_{MERN}), as derived from the yield-to-nitrogen response relationships, and price ratios (P_R) for the year of harvest. With the exception of ENTEC used in the CTF treatment, the yield-to-nitrogen responses were not significant when a quadratic model was fitted to the data, which was observed in both traffic systems (P>0.05). Despite this, responses were significant at a 10% probability level in non-CTF × urea, and CTF × UAN. Yield-to-N responses were also tested using a linear function, and the responses were not significant for both traffic systems and the three fertiliser materials (P>0.05), with the exception of the CTF × ENTEC (Yield = 2742 + 2.7 N_{Rate}, R^2 = 0.93, P = 0.033, SE = 113), and non-CTF × urea (Yield = 2483 + 2.2 N_{Rate}, R^2 = 0.92, P = 0.037, SE = 93) **Table 5.2 [Appendix C.1]**.

For sorghum, with the exception of urea under CTF, yield-to-nitrogen responses were not significant when quadratic models were fitted to the data, which were observed in both traffic systems (P > 0.05). Despite this, responses were significant at a 10% probability level in non-CTF × UAN (**Table 5.3**). By eliminating the quadratic term from the model and converting to the linear, and subsequently re-running the analysis, yield-to-N responses relationships response remained not significant when the three fertiliser materials were applied for both traffic systems (P > 0.05) as shown in **Table 5.4 [Appendix C.2]**. At the optimum N rate, the corresponding yields (Y_{MERN}), CTF was 24% higher compared with non-CTF (mean values of 23.72 and 18.17 kg kg^{-1}, respectively).

Despite this, quadratic functions may be justified as all responses produced acceptable fits ($R^2 \geq 79$) and ($R^2 \geq 88$) for wheat and sorghum, respectively, with all fertiliser formulations under both traffic systems. Therefore, it can be argued that quadratic models provide a more satisfactory biological description of the yield-to-N response, and therefore may be used despite non-statistical significance of the quadratic term (Shaohua et al., 1999).

Table 5.1. The calculated most economic rate of nitrogen (N_{MERN}) in wheat crop and the theoretical application rate for maximum yield response (N_{MAX}) for CTF and non-CTF systems, where (P_{Grain}) price of grain; (P_N), price of nitrogen; (R_P), price ratio; (SE), Standard Error; (N_{MAX}), maximum nitrogen; (Y_{MAX}), maximum yield; (MERN), most economic rate of nitrogen; (Y_{MERN}), crop yield at MERN.

Treatments		P_{Grain}	P_N	R_P	Response	P-value	SE	R^2-value	N_{MERN}	Y_{MERN} (SD)	N_{MAX}	Y_{MAX}
		(AUD kg^{-1})		- -	- - -	- - -	- - -	- - -	(kg ha^{-1})			
non-CTF	UAN	0.28	0.77	2.8	$y = 2340 + 9.1x - 0.04x^2$	0.45	312	0.79	124	3079 (394)	178	3153
	ENTEC	0.28	0.96	3.4	$y = 2373 + 5.9x - 0.01x^2$	0.32	166	0.90	93	2804 (307)	224	3028
	Urea	0.28	0.75	2.7	$y = 2419 + 4.0x - 0.01x^2$	0.08	42	0.98	107	2778 (286)	320	3061
CTF	UAN	0.28	0.77	2.8	$y = 2682 + 9.2x - 0.02x^2$	0.09	65	0.99	143	3538 (412)	204	3622
	ENTEC	0.28	0.96	3.4	$y = 2662 + 5.1x - 0.01x^2$	0.03	20	0.99	106	3117 (366)	321	3485
	Urea	0.28	0.75	2.7	$y = 2693 + 8.7x - 0.03x^2$	0.20	116	0.95	117	3358 (539)	168	3427

UAN = Urea ammonium nitrate (solution, 32%N),

ENTEC = urea treated with 3,4-dimethyl pyrazole phosphate (DMPP, 46% N), and

Urea (46% N)

Table 5.2. Wheat grain yield-to-nitrogen responses relationships tested by using linear functions. SE is a Standard Error.

Treatments		Response	P-value	SE	R^2
non-CTF	UAN	$y = 2598 + 1.4x$	0.52	424	0.22
	ENTEC	$y = 2504 + 1.9x$	0.81	218	0.66
	Urea	$y = 2483 + 2.1x$	0.03	93	0.92
CTF	UAN	$y = 2907 + 2.5x$	0.23	323	0.59
	ENTEC	$y = 2742 + 2.7x$	0.03	113	0.93
	Urea	$y = 2957 + 0.8x$	0.63	382	0.10

Table 5.3. The calculated most economic rate of nitrogen (N_{MERN}) in sorghum crop and the theoretical application rate for maximum yield response (N_{MAX}) for CTF and non-CTF systems, where (P_{Grain}) price of grain; (P_N), price of nitrogen; (R_P), price ratio; (SE), Standard Error; (N_{MAX}), maximum nitrogen; (Y_{MAX}), maximum yield; (MERN), most economic rate of nitrogen; (Y_{MERN}), crop yield at MERN.

Treatments		P_{Grain}	P_N	R_P	Response	P-value	SE	R^2-value	N_{MERN}	Y_{MERN} (SD)	N_{MAX}	Y_{MAX}
		(AUD kg^{-1})		- -	- - -	- - -	- - -	- - -	(kg ha^{-1})			
non-CTF	UAN	0.23	0.77	3.3	$y = 1029 + 13.5x - 0.04x^2$	0.07	69	0.99	117	2012 (504)	156	2077
	ENTEC	0.23	0.96	4.2	$y = 1062 + 7.6x - 0.02x^2$	0.16	80	0.97	73	1491 (283)	163	1678
	Urea	0.23	0.75	3.3	$y = 1067 + 11.4x - 0.04x^2$	0.13	102	0.98	111	1884 (429)	156	1957
CTF	UAN	0.23	0.77	3.3	$y = 1527 + 27.9x - 0.08x^2$	0.11	200	0.98	152	3902 (1053)	173	3937
	ENTEC	0.23	0.96	4.2	$y = 1575 + 16.1x - 0.04x^2$	0.34	412	0.88	140	2998 (696)	190	3101
	Urea	0.23	0.75	3.3	$y = 1488 + 23.5x - 0.07x^2$	0.01	24	0.99	142	3385 (868)	165	3423

UAN = Urea ammonium nitrate (solution, 32%N),

ENTEC = urea treated with 3,4-dimethyl pyrazole phosphate (DMPP, 46% N),

Urea (46% N)

Table 5.4. Sorghum grain yield-to-nitrogen responses relationships tested by using linear functions. SE is a Standard Error.

Treatments		Response	P-value	SE	R^2
non-CTF	UAN	$y = 1461 + 0.5x$	0.87	612	0.02
	ENTEC	$y = 1294 + 0.6x$	0.73	333	0.07
	Urea	$y = 1432 + 0.5x$	0.81	520	0.02
CTF	UAN	$y = 2336 + 3.7x$	0.55	1151	0.20
	ENTEC	$y = 1999 + 3.4x$	0.37	667	0.39
	Urea	$y = 2203 + 2.1x$	0.69	1012	0.10

1.5.2. Gross margins (GM)

Gross margin calculations for wheat were approximately 8% higher in CTF compared with non-CTF, if shallow tillage is practised, and about 4% higher if zero-tillage is practised ($P > 0.05$). Differences in gross margins between fertilisers type were mainly due to differences in the cost of N, particularly for ENTEC (AUD0.96 kg^{-1} N). The impact of fertiliser-N cost on gross margin was, therefore, higher for the non-CTF system because of overall lower yield (**Table 5.5**).

Table 5.5. Gross income (GI), total variable cost (TVC), and gross margin (GM) obtained from winter wheat based on the MERN and Y_{MERN} presented in Table 5.1. Constant variable cost is AUD144.45 ha^{-1}. Use AUD1 ≈ USD 0.75 for conversion.

Treatments		GI (AUD ha^{-1})		Fertiliser Cost	TVC	GM (AUD ha^{-1})	
		ZT[1] (45%)	ST[2] (65%)	AUD ha^{-1}	AUD ha^{-1}	ZT[1] (45%)	ST[2] (65%)
non-CTF	UAN	933	907	137	281	652	626
	ENTEC	833	815	131	275	558	540
	Urea	867	834	121	265	602	569
CTF+ZT	UAN	971		151	295	676	
	ENTEC	860		142	286	574	
	Urea	916		128	272	644	

[1] ZT when zero-tillage is practised; and [2] when shallow tillage is practised. [2] Rural Solutions, S 2017

For sorghum, the GM was estimated using the same approach that used for wheat, but without the additional cost of Granulock Starter fertiliser. The gross margin in the CTF treatment increased by approximately 34% and 25% compared with non-CTF ($P>0.05$), when a shallow and zero tillages are practised, respectively. For the assumption of practicing shallow tillage with CTF treatment, the differences were significant at a 10% probability level (**Table 5.6**). Differences in GM between fertiliser types are mainly due to differences in the cost of N, particularly for ENTEC, which indicated approximately AUD1000 per ton. The impact of fertiliser-N cost on gross margin was, therefore, higher for the non-CTF system due to overall lower yield.

Given current price ratios (nitrogen-to-grain prices) that reported in **Table 5.1 and 5.3**, and fertiliser formulations used, gross margin penalties of up to AUD50-100 per ha may be incurred in non-CTF systems compared with CTF when zero-tillage is practised, and penalties may double when shallow tillage is practised. Further economic outcomes (GM) that may be expected from reduced wheeled areas through combined ZT with CTF treatment, which was confirmed by (Vermeulen and Chamen, 2010; McHugh et al., 2009; McPhee et al., 2015). The prices of crops are the same for both traffic treatments and were taken at the harvest season of 2015-2016. These were AUD0.28 and 0.23 kg^{-1} for wheat and sorghum, respectively. Changes in the price of grain would affect gross margin due to a higher sensitivity of GM to the price of grain yield compared to the price of nitrogen. This finding was also agreed with other work conducted by Antille et al., (2017).

Table 5.6. Gross income (GI), total variable cost (TVC), and gross margin (GM) obtained from sorghum based on the MERN and Y_{MERN} presented in Table 5.3. Constant variable cost is AUD 169.11 ha^{-1}. Use AUD1 ≈ USD 0.75.

Treatments		GI (AUD ha^{-1})		Fertiliser Cost	TVC[2]	GM (AUD ha^{-1})	
		ZT[1] (45%)	ST[2] (65%)	AUD ha^{-1}	AUD ha^{-1}	ZT (45%)	ST (65%)
non-CTF	UAN	702	615	99	268	434	347
	ENTEC	534	464	79	248	286	216
	Urea	623	554	92	261	362	293
CTF+ZT	UAN	832		126	295	537	
	ENTEC	638		143	312	326	
	Urea	727		115	284	443	

[1] ZT when zero-tillage is practised; and [2] when shallow tillage is practised, [2] Rural Solutions, S 2017

Fertiliser nitrogen formulations and rates that used in the simulated crops to calculate the modelled yield (**Section 4.3.2**) were calibrated based on the MERN calculated in this section for urea (**Tables 5.1, 5.3**) for wheat and sorghum, respectively. Therefore, the simulated yields were obtained for N inputs equivalent to MERN, and analyses run for long-term (20 years for wheat and 21 years for sorghum), respectively. Based on the mean price of the crops and urea-N in the period of (1995-2017) (**Figures 5.1; 5.2; and 5.3**), the gross margins were determined annually for the tested crops (**Figure 5.4).**

1.5.3. Long-term impact of CTF on gross margin

Long-term analyses showed in **Figure 5.4** indicated that the value of GM can be affected by two main factors. The first one was the grain yield, which was obtained from the long-term modelling of crops using APSIM **(Section 4.4)**. Differences in grain yield between the modelled years are explained by rainfall, the distribution of rainfall within the season and soil water availability. For example, between 2000 and 2005 (for both traffic systems), simulated yields were below average, but despite this, they received similar amounts of rainfall compared to the years that yielded above average (**Chapter 4**). This was attributed to the amount of rainfall in the affected seasons was received in a short period, which can be increased runoff and decreased total drain of water particularly in a compacted soil. The cost of fertiliser also had a significant effect on crop GM (**Figures 5.2**) and (**Figure 5.3)**.

In wheat, the long-term mean crop GM in CTF was 15% higher than non-CTF (**Figure 5.4a**), and the difference between the two traffic treatments was higher by (AUD238 ha^{-1}) in sorghum (**Figure 5.4b**). In sorghum, the GM was negative by approximately AUD100 ha^{-1} in several years (200-2007 and 2010). Therefore it can be concluded that the summer crop was more affected by soil compaction than the winter crop due to the high chance of water evaporation during the Summer season, particularly for the top layer, which is considered the important layer for crops that planting in compacted soils (non-CTF system). It was assumed that the long-term variable costs are the same over the years of the analysis (1995-2015). This significant simplification analysis is simply to reflect CTF versus non-CTF and to show the relative differences between the two traffic treatments.

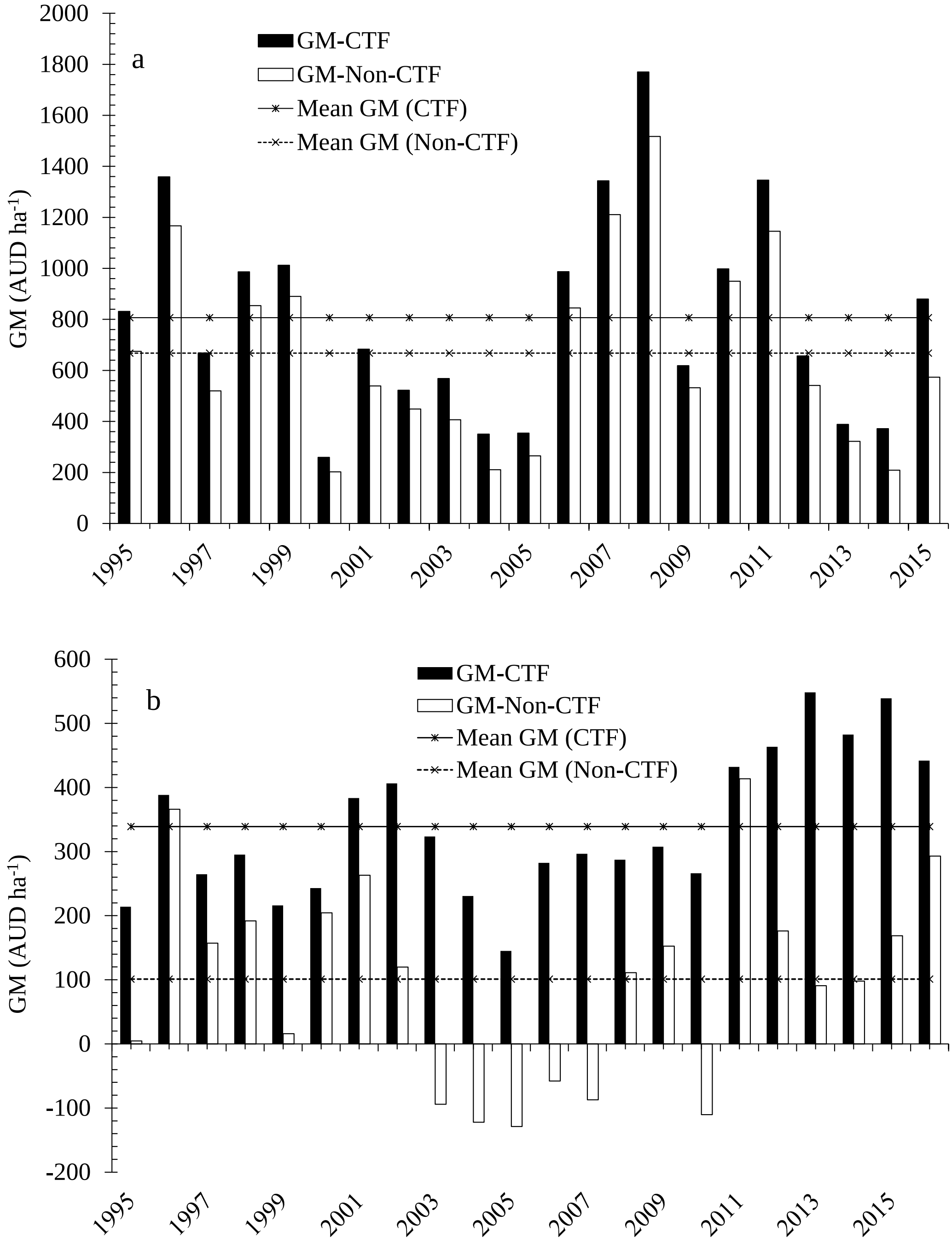


Figure 5.4. Long-term gross margins (1995-2016) of wheat (a) and sorghum (b) based on the simulated yields for CTF and non-CTF systems.

Most of the Australian growers are applying urea to their crops. This research investigated other fertiliser formulations as an alternative option to reduce the risk of the higher N application rates to the environment through losses by denitrification, volatilisation leaching or runoff. Some of these formulations have potential to reduce environmental losses, for example, ENTEC fertiliser formulation has an ability to reduce N losses mainly in the form of nitrous oxide emissions. There might be a need in future to comply with more stringent environmental regulation to reduce the environmental losses in the cropland, and one way of doing that is by using more efficient fertiliser formulation such as ENTEC. A sensitivity analysis was conducted to know when a particular fertiliser formulation becomes non economical depending on the price and the N application rates.

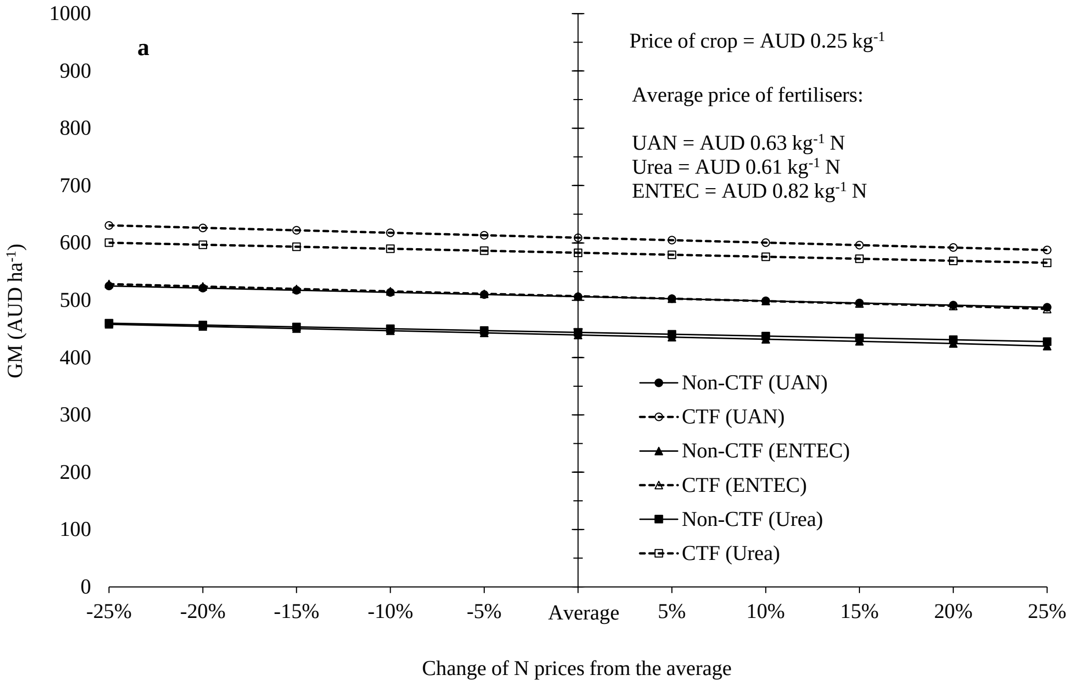
In general, a sensitivity analysis was conducted (**section 1.5.4**) to which investigated the changes in the crop gross margin as a result of changes in the price of nitrogen and the grain. It provided an indication of the effect that these changes can have on the gross margin of the crop depending upon the fertiliser type used. The sensitivity analyses undertaken also provided an indication of the level of financial compensation needed if changes in the price of the grain or N fertiliser occur.

1.5.4. Sensitivity analyses

The sensitivity analyses **(Figure 5.5 and 5.6)** showed that, regardless of the fertiliser type, gross margins are more sensitive to changes in the price of grain than changes in the price of nitrogen. For example, for wheat (**Figure 5.5b**) the results showed that a 40% increase in the price of grain (from AUD0.25 to 0.35 per kg) leads to an increase in GM at (UAN) by up to 35% for both traffic treatments whereas a 25% increase in the price of nitrogen led to a decrease in GM_{UAN} of about 2% in CTF and 3.5% in non-CTF. Similar differences are also the case for the other two fertiliser types (**Figure 5.5a**). In sorghum crop, a 40% increase in the price of grain (above the average) resulted in GM_{UAN} being increased by 40% in CTF and 55% in non-CTF (**Figure 5.6b**). By contrast, a 25% increase in the price of N decreased GM_{UAN} by approximately 5% in both traffic treatments (**Figure 5.6a**). This finding agrees with earlier work by Antille et al., (2017).

Clearly, the economic result (gross margin) is significantly dependent on the soil (physical) conditions. Enhancing soil properties by reducing the area of land affected by compaction such as in CTF, leads to increased return from the fertiliser applied, i.e., increase use efficiency.

The sensitivity analyses also highlighted the need to manage the crop efficiently in order to maximise grain yield. In managing the crop, attempts should be made not only to reduce input costs, including nitrogen fertiliser but also to optimise the use of resources. A greater economic return from the crop may be expected when grain yield is increased as a result of more effective agronomic management.



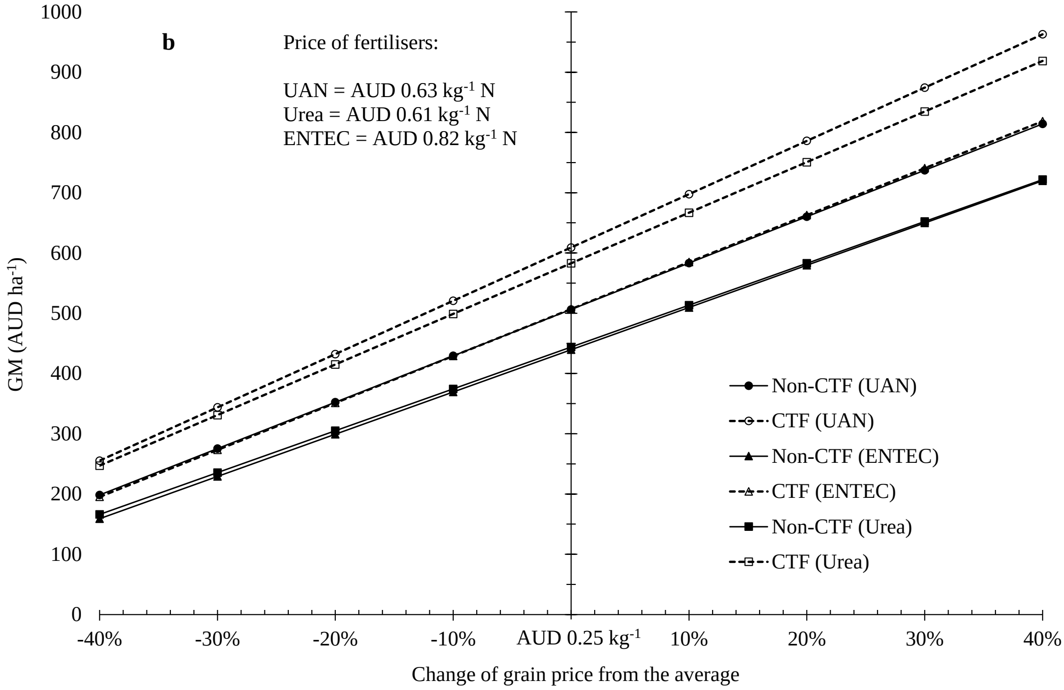
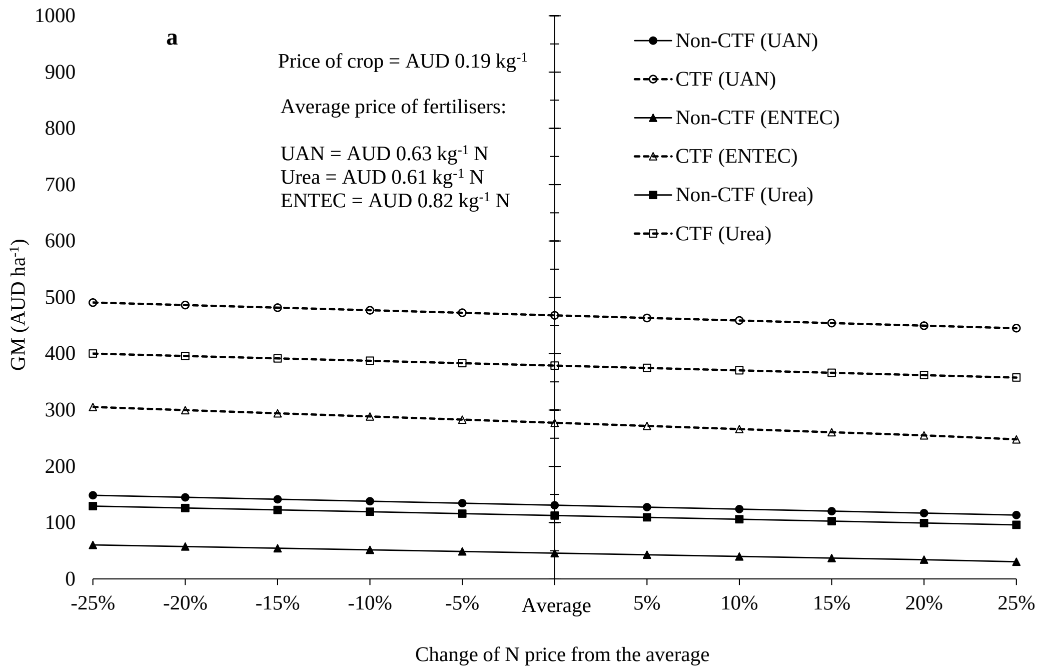


Figure 5.5. Sensitivity analyses for wheat crop (a) ± changes in the price of N fertilisers and the price of crop are constant (b) ± changes in the price of grain and the price of fertilisers are constant. The averages price of N and grain were for the period 1995-2015 and predicted values up to 2020.



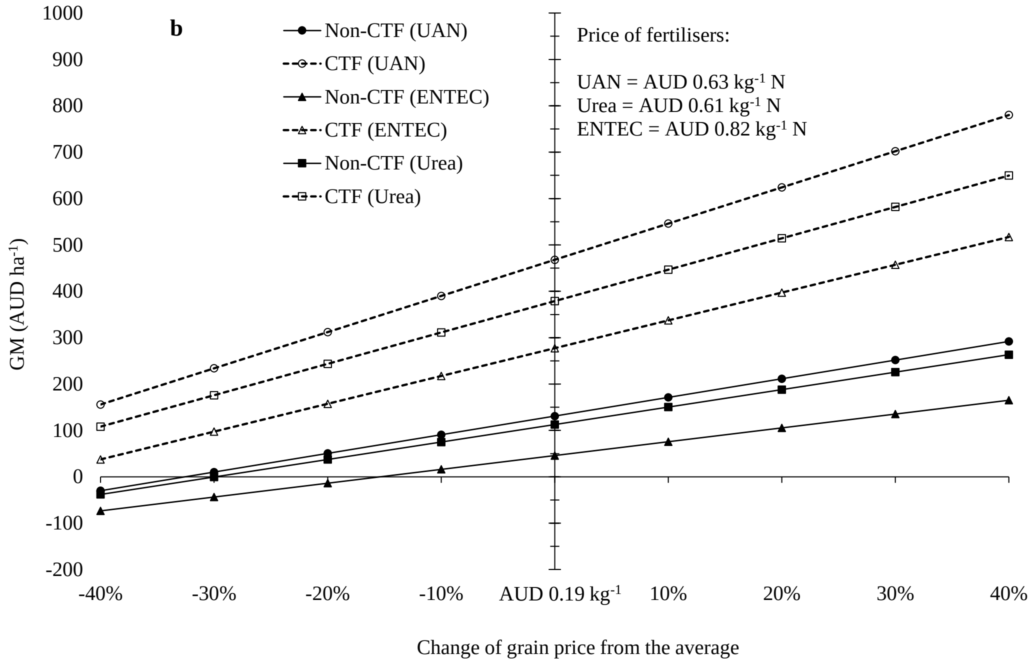


Figure 5.6. Sensitivity analyses for sorghum crop (a) ± changes in the price of N fertilisers and the price of crop are constant (b) ± changes in the price of grain and the price of fertilisers are constant. The averages price of N and grain were for the period 1995-2015 and predicted values up to 2020.

Based on the crop responses to applied fertiliser, it is possible to provide estimates of the MERN and Y_{MERN} in relation to the changes in the price ratio (R_P). The analysis shown in **Figures 5.3-5.6** also implies a sensitivity analysis to R_P for the range of nitrogen and grain prices investigated. In this respect, the values of MERN and their correspondent Y_{MERN} were re-calculated from the response curves for each price ratio (**Tables 5.7; 5.8; 5.9; and 5.10**).

The changes in the price of nitrogen were calculated using the same approach that used for changes in the price of crops. The price ratios used were between 1.8 and 4.1 based the price of nitrogen changed ±25%, at the price of wheat equivalent to AUD0.25 kg^{-1} **(Tables 4.7)**. For sorghum, the price ratios ranged from 2.4 to 5.4 at AUD0.19 kg^{-1} price of grain (**Table 4.9**). Based on the variables of price ration, two approaches were used to facilitate this analysis. The first technique was to determine the R_P is, provided that the price of crop remained constant (**Table 5.7** for wheat and **Table 5.9** for sorghum), on the contrary, the price of N remained unchanged in the second one (**Table 5.8** for wheat and **Table 5.10** for sorghum).

A reduction in P_N or/and an increase in P_C will change the R_P ratio, which in turn will allow a larger nitrogen rate to be applied and thus an increase in the expected crop yield (Y_{MERN}). Since an increment in grain yield has a more significant effect on gross margin than any reduction in the cost of nitrogen fertiliser, the resultant is that the crop's gross margin is increased. The example given uses UAN to further explain the sensitivity analyses. By reducing the price of nitrogen by 25%, the MERN values almost approached N_{MAX} and so does Y_{MERN} which approximately Y_{MAX}. for wheat, the price of nitrogen P_N=0% change, the MERN was lower than N_{MAX} by about 27% while the difference between Y_{MERN} and Y_{MAX} was only some 2% in both traffic treatments **(Table 5.7)**. With increases in the price of nitrogen (by e.g., 25%), the MERN reduced by 9% compared to the MERN at the average price of nitrogen (AUD0.63, 0.82, 0.61 kg^{-1} for UAN, ENTEC, urea respectively), whereas the Y_{MERN} only changed by 1.5% for both traffic treatments.

The sensitivity analyses that were undertaken also quantified of the MERN and Y_{MERN} for wheat and sorghum, based on changes in the price of grain yields (P_C) for both traffic treatments **(Table 5.8)** and (**Table 5.10),** respectively. To facilitate the analysis, the sensitivity of the MERN for the used fertiliser formulations, and their corresponding yields was analysed by ±30% changes in the grain prices instead of ±40% due simply to avoiding the poor economic outcome (minus).

A fluctuation of wheat prices by 30% above and down the average (0.25 AUD per kg) increases and decreases the price ratios for the three fertiliser formulations by approximately 30%. The assumption for increased price of wheat showed that the MERN for UAN, ENTEC and urea have to be increased above average respectively by 13, 47, 11 kg ha^{-1} in CTF and 11, 27 and 41 kg ha^{-1} in non-CTF to approach the corresponding yields (Y_{MERN}). The MERN and Y_{MERN} were more sensitive to the reduction than the increase in the price of grain. For instance, Y_{MERN} and MERN decreased by 350 kg ha^{-1} and 88 kg ha^{-1}, respectively, when ENTEC was applied to CTF plot planted by wheat **(Table 5.8)**.

With regards to changes in the price of sorghum grain yield **(Table 5.10)**, as reported for wheat, similar scenarios were estimated for increases and decreases in the price of sorghum in relation to the average price (AUD0.19 per kg). For example, the MERN and Y_{MERN} were increased by 5 kg ha^{-1} N (UAN) and 14 kg ha^{-1}, respectively, in CTF when the price of grain increased by 30%, whereas 10 kg ha^{-1} N (UAN) and ≈40 kg ha^{-1} in the same traffic system if the price of grain decreased by 30%. Despite the MERN were higher in CTF system by approximately 25-50 kg ha^{-1} N for the three fertilisers, the Y_{MERN} were significantly lower by 1400-1900 kg ha^{-1} non-CTF compared with CTF when the analysis assuming that the price of grain increased by 30%. Therefore, the sensitivity analyses can be concluded that the lower performance of non-CTF compared to CTF traffic system was affected by soil physical properties represented by a poorer agronomic response to fertiliser as a result of high bulk density and penetration resistance of non-CTF treatments.

Table 5.7. Price ratio (based on ± change in the price of nitrogen) and corresponding MERN (kg ha^{-1}) and Y_{MERN} (kg ha^{-1}) for wheat crop under controlled and non-controlled traffic systems. The mean price of N fertilisers are 0.63, 0.82, 0.61 AUD per kg for UAN, ENTEC, and urea respectively, and the price of crop is 0.25 AUD per kg.

Change in the price of N	R_P			CTF						non-CTF					
				MERN			Y_{MERN}			MERN			Y_{MERN}		
	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea
+25%	3.1	4.1	3.0	135	63	110	3514	2954	3339	116	67	83	3050	2707	2711
+20%	3.0	3.9	2.9	138	76	112	3522	3005	3345	118	75	93	3057	2738	2741
+15%	2.9	3.8	2.8	140	86	114	3530	3043	3352	120	81	103	3064	2761	2770
+10%	2.8	3.6	2.7	143	96	117	3538	3080	3358	123	87	113	3070	2784	2797
+ 5%	2.6	3.4	2.6	146	106	119	3545	3115	3364	125	93	123	3076	2806	2823
Average	**2.5**	**3.3**	**2.4**	**148**	**116**	**121**	**3552**	**3149**	**3370**	**127**	**99**	**133**	**3082**	**2826**	**2848**
- 5%	2.4	3.1	2.3	151	126	123	3558	3181	3376	130	105	143	3088	2846	2872
-10%	2.3	3.0	2.2	154	136	126	3564	3211	3381	132	112	153	3093	2865	2895
-15%	2.2	2.8	2.1	156	146	128	3570	3240	3386	134	118	163	3099	2883	2916
-20%	2.0	2.6	2.0	159	156	130	3576	3267	3390	137	124	173	3103	2899	2936
-25%	1.9	2.5	1.8	162	166	133	3581	3293	3395	139	130	183	3108	2915	2955

Table 5.8. Price ratio (based on ± change in the price of grain) and corresponding MERN (kg ha^{-1}) and Y_{MERN} (kg ha^{-1}) for wheat crop under controlled and non-controlled traffic systems. The price of N fertilisers are 0.63, 0.82, 0.61 AUD per kg for UAN, ENTEC, and urea respectively, and the mean price of crop is 0.25 AUD per kg.

Change in the price of grain	**R_P**			**CTF**						**non-CTF**					
				MERN			Y_{MERN}			MERN			Y_{MERN}		
	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea
+30%	1.9	2.5	1.9	161	163	132	3580	3286	3394	138	128	179	3107	2911	2949
+20%	2.1	2.7	2.0	158	150	129	3573	3251	3388	135	120	166	3101	2890	2924
+10%	2.3	3.0	2.2	153	134	125	3564	3207	3380	132	111	151	3093	2862	2891
Average	**2.5**	**3.3**	**2.4**	**148**	**116**	**121**	**3552**	**3149**	**3370**	**127**	**99**	**133**	**3082**	**2826**	**2848**
-10%	2.8	3.6	2.7	142	93	116	3535	3070	3357	122	85	110	3068	2778	2790
-20%	3.2	4.1	3.1	134	64	109	3512	2959	3338	115	68	82	3048	2710	2709
-30%	3.6	4.7	3.5	124	28	101	3479	2799	3311	107	45	45	3019	2611	2590

Table 5.9. Price ratio (based on ± change in the price of nitrogen) and corresponding MERN (kg ha^{-1}) and Y_{MERN} (kg ha^{-1}) for sorghum crop under controlled and non-controlled traffic systems. The mean price of N fertilisers are 0.63, 0.82, 0.61 AUD per kg for UAN, ENTEC, and urea respectively, and the price of crop is 0.19 AUD per kg.

Change in the price of N	R_P			CTF						non-CTF					
				MERN			Y_{MERN}			MERN			Y_{MERN}		
	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea
+25%	4.1	5.4	4.0	147	126	136	3885	2927	3367	108	46	101	1979	1362	1848
+20%	3.9	5.2	3.8	148	129	138	3889	2944	3371	110	52	104	1987	1392	1856
+15%	3.8	4.9	3.7	149	131	139	3892	2956	3375	112	56	106	1994	1415	1864
+10%	3.6	4.7	3.5	150	134	140	3896	2968	3379	114	61	108	2000	1437	1872
+ 5%	3.5	4.5	3.4	151	136	141	3899	2980	3383	116	65	110	2007	1458	1880
Average	**3.3**	**4.3**	**3.2**	**152**	**139**	**142**	**3903**	**2991**	**3387**	**117**	**70**	**112**	**2013**	**1478**	**1887**
- 5%	3.2	4.1	3.1	153	141	143	3906	3001	3390	119	74	114	2019	1497	1893
-10%	3.0	3.9	2.9	154	144	144	3909	3011	3393	121	79	116	2025	1515	1900
-15%	2.8	3.7	2.7	155	146	145	3912	3020	3396	123	84	119	2030	1532	1906
-20%	2.7	3.5	2.6	156	149	146	3914	3029	3399	125	88	121	2035	1548	1912
-25%	2.5	3.3	2.4	157	151	147	3917	3038	3402	126	93	123	2040	1564	1917

Table 5.10. Price ratio (based on ± change in the price of crop) and corresponding MERN (kg ha^{-1}) and Y_{MERN} (kg ha^{-1}) for sorghum crop under controlled and non-controlled traffic systems. The price of N fertilisers are 0.63, 0.82, 0.61 AUD per kg for UAN, ENTEC, and urea respectively, and the mean price of crop is 0.19 AUD per kg.

Change in the price of grain	R_P			CTF						non-CTF					
				MERN			Y_{MERN}			MERN			Y_{MERN}		
	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea	UAN	ENTEC	Urea
+30%	2.5	3.3	2.4	157.1	151.0	147.3	3917	3037	3402	126.6	92.3	122.7	2040	1562	1916
+20%	2.7	3.6	2.7	155.7	147.6	145.8	3914	3026	3398	124.0	86.1	119.8	2033	1541	1909
+10%	3.0	3.9	2.9	154.1	143.6	144.1	3909	3011	3393	121.0	78.8	116.3	2025	1514	1899
Average	**3.3**	**4.3**	**3.2**	**152.1**	**138.8**	**141.9**	**3903**	**2991**	**3387**	**117.4**	**69.9**	**112.2**	**2013**	**1478**	**1887**
-10%	3.7	4.8	3.6	149.7	132.8	139.3	3894	2963	3378	112.8	59.0	107.0	1997	1428	1869
-20%	4.2	5.5	4.1	146.7	125.2	136.0	3882	2924	3365	107.1	45.1	100.4	1975	1356	1844
-30%	4.8	6.3	4.7	142.7	115.3	131.6	3864	2866	3346	99.6	27.0	91.9	1941	1250	1806

5.5. Conclusions

Based on the data of field trials that were discussed in **Chapter 3** and the modelling of crop performance in **Chapter 4**, this chapter analysed the economic impact of controlled and non-controlled traffic systems by determining the most economic rate of nitrogen (MERN) for a range of fertiliser types, the corresponding grain yields (Y_{MERN}), and gross margins (GM). A sensitivity analysis was also conducted by assuming changes in the price of nitrogen and grain for the period 1995-2016 by 25% and 40%, respectively. The main conclusions derived from **Chapter 5** are summarised below:

- The MERN in non-CTF were lower by 13% (19 kg ha^{-1} N), 12% (13 kg ha^{-1} N), and 9% (10 kg ha^{-1} N) compared with CTF treatment when UAN, ENTEC, and urea were applied to wheat crop, respectively. The corresponding crop yield (Y_{MERN}) under CTF was higher by 13% (459 kg ha^{-1}) for UAN, 10% (313 kg ha^{-1}) for ENTEC, 17% (580 kg ha^{-1}) for urea. Response of sorghum crop to nitrogen application rates and soil conditions was higher compared to wheat in the Red soil. In sorghum, the economic yields were higher by 45-50% in the CTF for all fertiliser formulations compared to non-CTF even though the corresponding N rates (MERN) have indicated to be higher by few kilograms in CTF.
- Based on the MERN and Y_{MERN}, it can be concluded that the differences in the crop gross margins between the two traffic systems were increased when urea fertiliser was applied to both crops. In wheat crop, the GM was reduced by 50 and AUD33 ha^{-1} in non-CTF when UAN and ENTEC were applied respectively, whereas the reduction has increased to AUD74 ha^{-1} when urea was applied. Although the overall comparisons between the soil the conditions regarding the

GM were reported to be higher in CTF treatment. In sorghum, the CTF was also provided more significant differences of GM_{urea} by (AUD150 ha^{-1}) compared with non-CTF. For both crops, further economic outcomes (GM) were received from reduced wheeled areas through combined ZT with CTF treatment compared with the results of the combination between shallow tillage and non-CTF.

- The sensitivity analyses indicated that regardless the fertiliser materials that were applied to the tested crops, the values of gross margins are more sensitive to changes in the price of grain than the price of nitrogen. A reduction in P_N as well as an increase in P_C will change the R_P ratio which in turn will allow a larger nitrogen rate to be applied and thus an increase in the expected crop yield (Y_{MERN}). In relation to the sensitivity analyses of the MERN and Y_{MERN}, these two values were more sensitive to the reduction in the price of grain for both crops than the increasing in the price of grain.

6. OVERALL DISCUSSION

6.1. Introduction

The results derived from the modelling work and the field studies and reported in previous chapters are integrated and holistically discussed in this chapter. This chapter also refers to some of the elements i.e., traffic farming systems and their effects on crop, nitrogen use efficiency and farm profitability. These elements were reviewed in the literature review which helped to set out the research aims and objectives. The aim of this chapter is to integrate the outcomes of this study in a comprehensive manner to be able to address the overall aim and objectives of this project. The relationship between the chapters of this dissertation is shown in **Figure 6.1**.

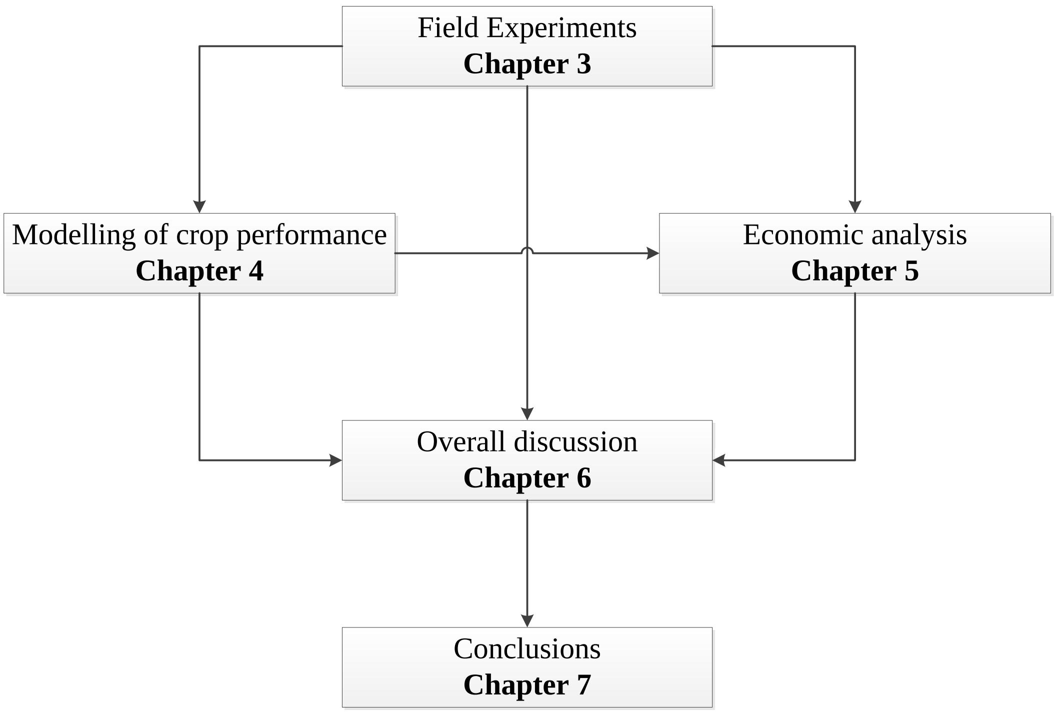


Figure 6.1. The relationship between the main chapters of this project.

6.2. Appraisal of controlled traffic farming

It is widely recognised that soil compaction induced by traffic of farm machinery results in deterioration of the soil physical properties and consequently, report that soil resources and functions are affected (Pagliai et al., 2003; Raper, 2005). A controlled traffic system provides a number of advantages in terms of enhancing both soil properties and crop productivity (Tullberg et al., 2001). Adoption of CTF in Australia, and particularly in Queensland, has demonstrated that farmers recognise the benefits of this system (Yule et al., 1998; Tullberg et al., 2007). Avoiding soil compaction by confining it to permanent traffic lanes through using controlled traffic farming (CTF)has not been investigated to the extent addressed in this work.

The research reported in this thesis was based upon the need to further quantify the benefits associated with use of CTF, specifically, with regards to N fertiliser use efficiency. Therefore, this research determined the effects of controlled and non-controlled traffic of farm machinery on the agronomic and economic performance of arable crops subjected to varying fertiliser nitrogen management strategies. This was achieved through a combination of field-scale experimentation and novel modelling approaches, as highlighted in the five objectives stated in **Section 1.1.2**.

6.2.1. Effect on soil physical and hydraulic properties

Soil compaction leads to soil structure degradation, which is strongly associated with changes in the soil physical properties such as porosity, bulk density and cone index (Coelho et al., 2000). These findings were also confirmed by results obtained in the current study. Compacted soil represented by the non-CTF traffic treatment resulted in higher bulk density and cone index, and lower total porosity.

Soil cone indices within this study were consistent with soil bulk density in both field experiments. The samples of cone indices were determined at moisture contents ranging from 10-16% (w w^{-1}), which were below the optimum moisture content (21.2%) based on the Proctor test. Proctor density values obtained in this work (1.7 g cm^{-3}) suggested that soil susceptibility to traffic compaction may be highest at moisture contents in the range of 20% to 30% (w/w). Therefore, the risk of soil damage due to compaction will be proportionally reduced when traffic occurs at moisture contents below plastic limit (Cresswell et al., 2016). Unsurprisingly, soil penetration resistance increases with decreasing soil water content (Lipiec, 2002). Cone indices were relatively higher compared to the resulting bulk density which may be due to the higher amount of iron oxide contained in the Red soils (Moody, 1994). The iron oxides, together with smaller amounts of free aluminium oxides (Moody 1994) and relatively high organic matter contents (Oades 1995), give Ferrosols their strongly developed structure. The other reason was given by Daddow and Warrington (1983), who reported that soils with a large amount of fine particles (silt and clay) will have smaller pore diameters and a higher penetration resistance at a lower bulk density than a soil with a large amount of coarse particles.

This study also showed that the CTF treatment stored more water in soil due to infiltration (approximately double those of the non-CTF), and hydraulic conductivity (20 times higher in CTF compared to non-CTF). In the present study, non-CTF treatment significantly reduced infiltration rate from 42 mm h^{-1} recorded in CTF to about 3 mm h^{-1} for non-CTF. Connolly et al. (1997) reported steady infiltration rates of 80 mm h^{-1} for bare virgin black Vertosols in Queensland, whereas infiltration rates of only 20 mm h^{-1} and 4–12 mm h^{-1} were found, respectively, by Silburn and Connolly (1995) and by Freebairn et al. (1984) for these soils when subjected to long-term cultivation. These results were also consistent with modelled data reported in chapter 5, and largely explained differences in yield, yield components and fertiliser use efficiency between both traffic treatments. Figures 4.5 and 4.7 showed that the annual runoff observed higher in non-CTF compared with CTF for wheat and sorghum, respectively (94 and 64 mm in CTF and 130 and 93 mm in non-CTF for wheat and sorghum, respectively). These observations agree with studies on black Vertosols (clay soil) dealing with functional relationships between traffic compaction, runoff generation, and effect on crop yield (e.g., Li et al., 2007, 2009).

Modelled water use efficiency (WUE) and runoff were significantly affected by compaction. For wheat, the simulated conditions of the CTF system reported up to 15% higher WUE compared with non-CTF (≈20.90 vs. 17.50 kg ha^{-1} mm^{-1} for CTF and non-CTF, respectively). For sorghum, WUE was 43% higher in CTF compared with the non-CTF treatment (≈8.40 vs. 4.80 kg ha^{-1} mm^{-1} for CTF and non-CTF, respectively), which was in the range of other studies conducted in Australia. In South Australia, French and Schultz (1984a) determined a mean value of 6.9 kg ha^{-1} mm^{-1}. Angus and van Herwaarden (2001) estimated 3.8 kg ha^{-1} mm^{-1} or 36% of simulated potential for mean district yields from the Wagga Wagga local government area in New South Wales. Sadras and Angus (2006) determined a mean WUE value of 8.3 kg ha^{-1} mm^{-1} from farms and 10.1 kg ha^{-1} mm^{-1} from experimental plots in the Mallee in South Australia. Yields at The Wagga Wagga Agricultural Research Institute achieved an average WUE of 15 kg ha^{-1} mm^{-1} with an x-intercept of 67mm (Cornish and Murray 1989). A similar WUE value (15.8 kg ha^{-1} mm^{-1}) was observed for modern wheat varieties from research plots at Merredin in Western Australia (Siddique et al. 1990). Antille et al. (2016) showed that hydraulic conductivity was up to ten times higher in non-trafficked soil compared with trafficked soil, which therefore agrees with these observations and other related research (e.g., Chyba et al., 2017). The ability of soil under simulated CTF conditions to hold water was reflected on modelled runoff, which was 45% higher in a non-CTF, particularly in the wetter years (>70th percentile; average rain for wheat and sorghum = 590 and 330 mm/season, respectively). This was attributed to smaller size of pores and fewer natural channel in a compacted soils subject to traffic, which agrees with Fleige and Horn (2000). Soil rehabilitation allows improved water infiltration, enhancing soil water storage and rainfall use efficiency, which translates into increased crop yield.

6.2.2. Effect on crop yield, yield components and fertiliser use efficiency

Figure 3.6 and **Figure 3.14** showed that there were reductions in grain yields harvested from non-CTF treatments across all fertiliser formulations and rates compared with CTF for wheat and sorghum, respectively. This showed that, on average, crop yield were 12% higher in winter wheat and 45% higher in sorghum in the traffic treatment representing CTF compared with non-CTF **(Chapter 3)**. This corresponded well with data reported in the literature on soil compaction (e.g., Arvidsson and Håkansson, 1996; Godwin, 2009; Tracy et al., 2012). Significant reductions in grain yields (up to 23% compared with non-compacted soil) were also found by Radford et al. (2001). Similar observations were obtained during a five year experiment conducted in Sweden, where about 12% decline in crop yield of spring barely was reported in compacted soil (Arvidsson and Håkansson, 1996), and this was confirmed in further trials by Lipiec and Hatano (2003). In the studies that investigated the effects of field traffic systems, mean yields were often increased by 5-20% in CTF system (Dickson and Campbell, 1990; Tullberg et al., 2007). Compaction tends to preclude this free exploration and the consequential reduction in water and nutrient uptake is often the cause of yield depression (Chamen et al., 2006). A study by Botta et al. (2007) on soybeans showed that a 60% reduction in traffic intensity at harvest led to increase grain yield by approximately 30% on average after three years. Improved soil conditions by reducing soil compaction through using controlled traffic technique can certainly improve plant water and nitrogen uptake, which subsequently improve grain yield as explained in the previous chapters.

As has been reported in the earlier chapters, sorghum (summer crop) was more affected by soil compaction than wheat (winter crop). The compacted soil created a poorer aeration status under wet conditions (above average rainfall) which would make it less appropriate for crops such as sorghum that tends to be more sensitive to the wheeled soil conditions than wheat. In wheat, grain yield is mainly determined by the number and the weight of grains (Slafer, 2003). These two components are affected by the size of the canopy and spike, and crop × environment interactions post-anthesis, respectively (Slafer, 2007). Figure 3.7b shows that the number of grains per m^2 was significantly higher in CTF compared with non-CTF treatment, which was also confirmed by (Slafer and Andrade, 1993). Higher grain yields are expected in crops that accumulated have higher biomass at maturity (Austin, 1982). Total aboveground biomass at pre-harvest, thousand grain weight (TGW), number of spikes and number of grains per m^2 within this work showed significant differences between traffic treatments, which therefore demonstrate differences in grain yield. The response to compaction of these yield components reflect the crop’s sensitivity to such compaction and the impact on fertiliser use efficiency. This latter effect linked to rainfall use efficiency (Sadras and Rodriguez, 2010). Harvest indices observed in fertilised plots within these experiments were in the range reported for other studies (e.g., Sinclair, 1998; Dai et al., 2016).

CHAPTER 6: OVERALL DISCUSSION

The reductions of nitrogen use efficiency (NUE) and agronomic efficiency (AE) in non-CTF treatments for wheat and sorghum may be attributed mainly to water stress through increased runoff and decreased infiltration rate. For wheat, fertiliser N recovery efficiency across region varied over a large range: 0.3 to 0.4 kg N taken up per kg N applied (30–40%) based on grain N alone (Ehdaie et al., 2010). Levels of fertiliser applications influence the grain yield and the total dry matter accumulation thereby affecting the nutrient demand (uptake/utilisation). Increasing applications of N from 0 to 300 kg ha^{-1} reduces overall N use efficiency and agronomic efficiency in wheat and sorghum. For wheat, nitrogen use efficiency at 300 kg ha^{-1} was 48% lower than 200 kg ha^{-1} for both traffic treatments. Such low N recoveries may be related to N losses from soil via denitrification, ammonia volatilization, and NO_3^--N leaching (Craswell and Vlek, 1979). Differences in NUE between treatments due to N uptake were also explained by both traffics effect on yield and total N in grain, as shown in Figure (3.10 and 3.11). The current result conforms with that of Antille et al. (2017) who reported that AE decreased with increasing N rates from 50 to 250 kg N ha^{-1}.

Although there were no significant differences in NUE between the three N fertiliser types, NUE in both traffic treatments increased in the order: UAN > urea > ENTEC, which was consistent with differences in grain yield and yield components between the three fertiliser types. Relatively low rainfall was received during the critical stages of wheat (from July to the end of August) (**Figure 3.1**), which may have affected grain yield negatively through reducing both number and weight of grains particularly in compacted soils (Håkansson and Lipiec, 2000).

Relative reduction of grain yield with a further increment in applied N above 200 kg ha^{-1} might be attributed to vegetative growth early on in the season when both water and nutritional (N) conditions where not limiting (Table 3.2 and 3.5 for wheat and sorghum, respectively). Later in the season, even though N supply in the 300 kg/ha treatments was not limiting, water and temperature became the limiting factors. Therefore, a higher initial biomass in those plots could not sustain an equally high grain yield level. Consequently, grain yield was affected to greater extent in those plots compared to the plots where lower N rates were applied. By contrast, these plots developed a smaller biomass early on in the season, consistent with the N supplied via fertiliser, and required less water to satisfactorily complete the season. The end result is that both the water (rainfall) and N (fertiliser) were optimised at a lower than the maximum investigated in this experiment, and denotes a significant effect of water x N interaction on grain yield. These finding was confirmed by Gaju et al. (2014) who reported that the environmental factors greatly influencing pre-anthesis accumulation of N (e.g., drought and higher temperature during spring of wheat crops) and subsequent remobilization of N as the crop approaches the grain-filling phase. Zemichael et al., (2017) have reported a decrease in grain yield with the application of higher doses above 69 kg N ha^{-1} caused by excess vegetative growth, decreased number of grains per spike and delayed senescence that may have resulted in low rates of grain filling.

The agronomic efficiency (AE) (kg extra grain produced/kg additional N applied) decreased by approximately 48% and 62% (UAN), 15%, and 35% (ENTEC), and 55 and 81% (urea) for the high N increment (100-200 and 200-300 kg N ha^{-1}, respectively) under CTF treatment. These findings were relatively consistent with Lester et al., (2016) who reported that AE decreased by 40% (Kingaroy) and 20% (Kingsthorpe) for the higher N increment (80–120 or 80–160 kg N/ha at Kingaroy and Kingsthorpe, respectively) compared with the first 80 kg N/ha applied at each location.

In sorghum (**Chapter 3**), yield data have confirmed the existence of ‘yield reduction’ on a crop grown in a non-CTF treatment by up to 40% compared with CTF, which agreed with results reported in the wheat experiment. The level of grain yield increase under non-compacted soil was within the range (30-55%) reported in numerous past studies (e.g., Radford et al., 2001; Hamza and Anderson, 2003; Sadras et al., 2005). Boone and Veen, (1994a) attributed the poor agronomic performance and nitrogen use efficiency in compacted soil to the limited supply of water, oxygen and nutrients from the soil to the root system or a limited activity of the root system. Which is confirm that fertiliser rate and formulation are unlikely to be beneficial if there is an underlying of soil compaction.

The transport of nutrients in the soil is affected by compaction, which normally reduced mass flow transport and diffusion coefficient at a given gravimetric water content (Kemper et al., 1971). The mass flow is driven by the plant uptake of water (Barber, 1962), which therefore and in relation to this study, non-CTF treatment had an indirect impact on nutrients uptake by plant as this traffic technique was reduced water use efficiency through increased soil compaction. Modelled water use efficiency and runoff are explained with further details in the next section.

6.2.3. Crop modelling

The ability to accurately represent random as well as controlled traffic conditions through modelling are difficult due to the differences in the management practices by different growers, and prevailing soil and climate conditions. This study rather mimics the overall resultant conditions from a non-CTF and CTF experiments from the current one year field study, and explores it to multiple years through hind-casting. The modelling results are thus best used to understand the effect on crop productivity and resource use efficiency (rainfall, fertiliser) of inter-year climate variability which was not possible to explore in these short-term field studies.

Modelled results (**Chapter 4**) suggested that soil compaction is likely to reduce crop yield and biomass over a long-term, similar to those found under short-term field studies. Simulated impacts of non-CTF treatment on soil water dynamics, crop growth, and yield were consistent with previous soil compaction studies conducted on Grey Vertosols in Queensland (e.g., Radford et al., 2000). The negative effects associated with soil compaction were a reduction in both biomass and yield, especially during below average rainfall conditions. Soil compaction reduces the sowing soil moisture, which is a key determinant of crop performance (Júnnyor et al., 2015). Successful dryland crop production, especially in arid and semi-arid regions, relies heavily on moisture stored at the time of sowing (Freebairn et al., 2009). Therefore, the modelled differences in water available at sowing will subsequent impact crop performance and decision-making associated with sowing (Kodur, 2017). Similarly, soil compaction will have negative impacts on runoff, which is due to reduced soil infiltration causing surface ponding followed by horizontal movement of water as runoff (Hammer et al., 2010; Acuña et al., 2015). Drier condition leads to greater reduction in fertiliser use efficiency, yield and biomass which is due to the higher water stress (Probert et al., 1995). Whereas, during high rainfall conditions, soil moisture will be less limiting to reduce crop yield and biomass under non-CTF and CTF, although runoff will be considerably higher. Hence, the amount of a particular nutrient taken up by the plant is dependent on the volume of water entering the roots and the concentration of the nutrient in the solution (Divito et al., 2011). Therefore, improved water use efficiency (WUE) in a CTF system resulted in higher NUE and grain yield.

As demonstrated in **Chapter 4,** drier conditions lead to greater reduction in yield and biomass which is due to the higher water stress (Probert et al., 1995). By contrast, during high rainfall events, soil moisture will be less limiting to reduce crop yield and biomass under non-CTF and CTF treatments, although runoff will be significantly higher (**Section 4.4**). A greater reduction of sorghum yield in soil compaction is evident from Júnnyor et al. (2015), which found that but involving wheat crop grown on Vertosol soils (Radford et al., 2001) and Antille et al. (2016) found a reduction in grain yield between 43% and 53%. These discrepancies can be attributed to the soil type where the wheat crop in this study was grown on Red Ferrosol which has a higher drainage porosity (SAT-DUL; Table 2) than Vertosol soils used by the others. A higher drainable porosity allowed greater infiltration even under compaction, leading to greater water loss in the form of drainage, which was otherwise used by the crops.

6.2.4. Economic considerations

The results of the regression analysis of fertiliser price (**Chapter 5**) suggested that the price of urea will increase by approximately 20% to 25% by the end of 2020 (Figure 5.1) (that is assuming a linear increase in fertiliser price at the rate projected by this study). The crop responses to nitrogen under soil conditions of both traffic systems were used to provide estimates of the most economic rate of nitrogen (MERN) from which the corresponding grain yields were calculated (Y_{MERN}). These were used to estimate gross margins (GM) for crops grown under controlled and non-controlled traffic systems. The changes in GM were investigated with regard to the price of the nitrogen (P_C) and the grain (P_C) and the relationship between them which is expressed by means of the price ration (P_R). The price ratio in this research was different between the treatments depending on (P_N) only, because the price of grain (P_C) was constant.

The grain prices for wheat and sorghum were taken at the harvest season of 2015 and

2016, respectively, which were equivalent to AUD0.28 kg^{-1} and AUD0.23 kg^{-1} (**Table 5.1 for wheat and Table 5.3 for sorghum in Chapter 5**). The gross margins were investigated for CTF and non-CTF systems, and the tillage systems that might be used with the traffic systems were also investigated. In Australia, zero tillage (ZT) is practised by most growers who have converted to the CTF system (Tullberg et al., 2007), with some exceptions (Dang et al., 2017). Therefore, ZT was considered in the assumption made for the CTF system. The gross margin for wheat crops was (≈ AUD 50 ha^{-1}) higher in CTF, which received (7%) greater gross income compared with a non-CTF system when shallow tillage is practised, and 4% when ZT is practised. In sorghum, given current price ratios (nitrogen-to-grain prices), and fertiliser formulations used, gross margin penalties of AUD75 per ha may be incurred in non-CTF treatments compared with CTF when zero-tillage is practised, and double that amount when shallow tillage is practised. The differences between CTF and non-CTF could be increased for the long-term of using CTF system, and if the comparisons was between CTF+ zero-tillage versus non-CTF+ conventional tillage. A modelling study of a Western Australian grain farm showed that CTF and zero-till could increase farm profitability by 50% compared to conventional random traffic and full tillage practices (Kingwell and Fuchsbichler 2011). Analysis of a Queensland grain cropping group showed increased cropping frequency and yield, and improved grain prices (due to greater yield reliability in dry years when prices are higher) had the potential to improve gross income by 44% (Bowman 2008). The combined benefits of the CTF system had the potential to almost double business profit for group members. Changes in crop price would affect the outcomes of gross margin due to a higher sensitivity of gross margin to the price of grain yield compared to the price of nitrogen (Figure 5.5 and Figure 5.6, for wheat and sorghum, respectively), which also agreed with other work conducted by Antille et al. (2017). Therefore, sensitivity analyses showed the major contributor to increased profit was increased yield.

This chapter has comprehensively discussed the findings from **Chapter 3**, **Chapter 4** and **Chapter 5**, and has addressed the overall aim and objectives formulated in **Chapter 1**. The overall conclusions coming from this research will be summarised in **Chapter 7**. These conclusions allow making a set of practical recommendations for future work that can be done in relation to controlled traffic farming system and fertiliser management.

7. CONCLUSIONS

This chapter summarises the overall conclusions of this study. Based on the research aims and objectives outlined in **Chapter 1**, the following conclusions were drawn. Detailed conclusions corresponding to the experimental and modelling works can be found in **Chapters 3 and 4**, respectively. The overall conclusions relating to the economic analyses are outlined in **Chapter 5**. Based on these conclusions, a set of practical recommendations is provided later **Chapter 8**.

7.1. Conclusions of the field experiments

The effect of two traffic systems, namely: CTF and non-CTF, and fertiliser management, namely: fertiliser type and N application rates, were investigated over two consecutive seasons included a winter crop (Wheat) and a summer crop (Sorghum). Modelling work using the Agricultural Production Systems Simulator (APSIM) was also conducted based on a novel approach developing in this study. This modelling work enabled predicting long-term impacts of soil compaction on crop productivity and water (rainfall) use efficiency. This modelling approach can be used to simulate such impacts in other cropping agro-climatic conditions, and to simulate “what if” scenarios in decision-making. The findings of these studies are summarised below:

7.1.1. Crop yield and fertiliser response

- Grain yields for wheat and sorghum were improved by up to 12% and 40%, respectively, in CTF compared with non-CTF. These results were consistent with measurements of crop yield components conducted in both crops. Total aboveground biomass and harvest index (HI) for wheat were 9% and 4% higher, respectively, in the traffic treatment representing CTF relative to that of the non-CTF. For sorghum, biomass and HI reported 25% and 19% higher in CTF compared with non-CTF.

- Nitrogen uptake in grain for wheat and sorghum were about 16% and 50%, respectively, higher in CTF compared with non-CTF, which was therefore reflected on nitrogen use efficiency calculations. Based on these relative differences, nitrogen use efficiency was approximately 45% and 60% higher in CTF compared with non-CTF for wheat and sorghum, respectively.
- For both wheat and sorghum, the relationship between crop yield and nitrogen application rate were explained by quadratic functions, which showed acceptable fits of the quadratic models fitted to the data ($R^2 \geq 0.79$ and $R^2 \geq 0.88$, respectively). These quadratic functions allowed the MERN (most economic rate of N) and the corresponding grain yields to be derived, which were subsequently employed to conduct the economic analyses.
- Maximum yields (Y_{MAX}) were 2%, 7%, and 8% higher than the optimum grain yields (Y_{MERN}) when UAN, ENTEC, and urea were applied to the wheat crop under both traffic systems. However, to reach the optimum yields, only 70%, 40% and 35% of the maximum N rates from UAN, ENTEC and urea respectively, were necessary for wheat in both traffic treatments.
- For sorghum, the highest values of grain yields were obtained by applying 25%, 55%, and 29% more nitrogen application rates from UAN, ENTEC and urea, respectively, in non-CTF treatment compared with 12%, 26% and 14% in the CTF.
- For both wheat and sorghum, relative differences in grain yields and yield-to-nitrogen responses between CTF and non-CTF were explained by compaction, to a greater extent than N fertiliser formulations. This confirmed that soil

compaction was the main factor influencing crop growth and N uptake and biomass partitioning into yield.

7.1.2. Soil physical and hydraulic properties

- Soil bulk density (SBD) measurements showed that the level of compaction in the top 300 mm of the soil profile was approximately 12% higher within the wheeled soil compared with the non-wheeled soil. This value was relatively consistent with the results of soil cone index within the same depth, which was up to 40% higher in the non-CTF treatment compared with CTF.
- Infiltration rates in the CTF treatment were approximately double those of the non-CTF treatment at any given time, which agreed with measurements of saturated hydraulic conductivity recorded in the top 100 mm (20 times higher in CTF compared with non-CTF). Such differences reflect the impact of traffic on soil porosity and the disruption in soil pore connectivity. These results were also consistent with APSIM modelled runoff, which was approximately 45% higher in the wheeled area and explained, to large extent, impaired N uptake and NUE in non-CTF treatment.

Yield response to N fertiliser appears to be strongly influenced by soil compaction. Where fertiliser use efficiency cannot be increased by simply changing fertiliser rate and/or formulation if there is an underlying problem of compaction. Therefore, in order to improve nitrogen use efficiency, the soil condition has to be currently (pre-requisite) improved.

7.2. Conclusions of the modelling study

- The results derived from the modelling work showed that in average rainfall years, yield reductions in non-CTF may be up to 13% and 38% for wheat and for sorghum, respectively, relative to the yields achieved in CTF. In below-average rainfall years, yield reductions in non-CTF can be up to 4% and 12% greater for wheat and sorghum, respectively, compared with the yield achieved in average rainfall years. In above-average rainfall years, differences in yield between CTF and non-CTF treatments were small, which showed that the effect of traffic compaction on crop yield is dependent on the seasonal effect of rainfall.
- Modelled WUE and runoff were also significantly affected by compaction. For wheat, the simulated conditions of the CTF system reported up to 15% higher WUE compared with non-CTF (≈20.90 vs. 17.80 kg ha^{-1} mm^{-1} for CTF and non-CTF, respectively). For sorghum, WUE was 45% higher in CTF compared with the non-CTF treatment (≈8.40 vs. 4.80 kg ha^{-1} mm^{-1} for CTF and non-CTF, respectively). Modelled runoff increased proportionally with an increase in total rainfall, these differences were significantly greater in non-CTF compared with CTF and for both crops. Overall, modelled runoff volumes in wheat and sorghum were, respectively, 28% and 45% higher in non-CTF compared with CTF. For both crops, WUE was relatively higher in drier years than wetter years, which should encourage growers to convert to CTF, particularly in dryland. This should also bring about great yield stability and higher cropping frequency due to improve water (rainfall) economy. Grain yields derived from this modelling study were in close agreement with data derived from field experimentation. Therefore, this modelling approach

appears to be robust and may be used to assist further studies in this space and to assist decision-making.

7.3. Conclusions of the economic analysis

- Based on the yield to nitrogen response relationships, the most economic rate of nitrogen (MERN), and their corresponding grain yields (Y_{MERN}), for wheat and sorghum, were as follows:

7.3.1. Wheat

i. If shallow tillage is practised:

a. Gross margins from the use of urea ammonium nitrate (UAN) were AUD676 ha^{-1} and AUD626 ha^{-1} in CTF and non-CTF systems, respectively.

b. Gross margins from the use of ENTEC® were AUD574 ha^{-1} and AUD540 ha^{-1} in CTF and non-CTF systems, respectively, and

c. Gross margins from the use of urea alone were AUD644 ha^{-1} and AUD569 ha^{-1} in CTF and non-CTF systems, respectively.

ii. If zero-tillage is practised

a. Gross margins from the use of urea ammonium nitrate (UAN) were AUD676 ha^{-1} and AUD 652 ha^{-1} in CTF and non-CTF systems, respectively.

b. Gross margins from the use of ENTEC® were AUD574 ha^{-1} and AUD558 ha^{-1} in CTF and non-CTF systems, respectively, and

c. Gross margins from the use of urea were AUD644 ha^{-1} and AUD602 ha^{-1} in CTF and non-CTF systems, respectively.

7.3.2. Sorghum

i. *If shallow tillage is practised:*

a. Gross margins from the use of urea ammonium nitrate (UAN) were AUD537 ha^{-1} and AUD347 ha^{-1} in CTF and non-CTF systems, respectively,

b. Gross margins from the use of ENTEC® were AUD326 ha^{-1} and AUD216 ha^{-1} in CTF and non-CTF systems, respectively, and

c. Gross margins from the use of urea were AUD443 ha^{-1} and AUD293 ha^{-1} in CTF and non-CTF systems, respectively.

ii. *If zero-tillage is practised*

a. Gross margins from the use of urea ammonium nitrate (UAN) were AUD537 ha^{-1} and AUD 434 ha^{-1} in CTF and non-CTF systems, respectively,

b. Gross margins from the use of ENTEC were AUD326 ha^{-1} and AUD286 ha^{-1} in CTF and non-CTF systems, respectively, and

c. Gross margins from the use of urea were AUD443 ha^{-1} and AUD362 ha^{-1} in CTF and non-CTF systems, respectively.

- The gross margin was more sensitive to the changes in the price of crop (P_C) than the price of nitrogen (P_N).
- While the gross margin analysis reflects specific conditions (year, site, prices) of this study, comparisons between the two traffic systems reflect potential financial penalties that may incurred when controlled traffic is not practised.
- Based on the field experiments, and the use of APSIM for simulating long-term effects of CTF on crop and soil, the main benefits of CTF are improved yield, yield stability and increased cropping frequency (increased opportunity for successful crop establishment), which therefore translates into increased

profitability. The modelling approach developed by this study can be applied to simulate long-term profitability scenarios, and therefore be used to assist growers in the decision-making process about potential conversion to CTF.

Results derived from this research confirm the hypotheses formulated prior to this study and therefore are supportive of increased adoption of CTF in South East Queensland in grain (dryland) cropping systems. However, to fully realise the production benefits of controlled traffic for crops such as canola on these soil types it may first be necessary to remove the underlying compaction generated by previous farming practices with deep ripping.

Based on the field experiments and modelling work, the research undertaken was able to draw practical recommendations for land manages to increase input use efficiency. Areas that merit further research are discussed in the next Chapter.

8. RECOMMENDATIONS AND FUTURE WORK

- Improved soil physical, mechanical and hydraulic properties, with the associated effects on yield and inter-annual yield stability, underpin the benefits of conversion to CTF. If compaction exists, this has to be removed prior to conversion to CTF. There are demonstrated synergisms when CTF is coupled with zero-tillage, both in terms of productivity and profitability, and positive impact on improved environmental performance. There is a need to investigate the cost-effectiveness of alternative traffic systems to CTF such as low (ground) pressure (LGP) vehicles. Recent research in the U.K. (e.g., Smith et al., 2013; Godwin et al., 2015) has shown that LGP systems can be effective in mitigating traffic compaction impacts, which has been demonstrated both in terms of improved agronomic performance and reduced tillage draft (energy). Such systems may offer an economical alternative to CTF, but their cost-effectiveness in the context of Australian agriculture requires investigation. This is an important practical consideration given that the cost of conversion to CTF is often perceived as one of the main barriers for adoption of this technology. Product warranty may be also lost when farm equipment is made CTF-compatible. Therefore, LGP systems may offer a readily available solution for mitigating compaction impacts in cropping systems such as cotton and sugarcane where other incompatibilities (e.g., crop row configuration) also exist.
- There is a need to review current fertiliser recommendations for arable crops established in CTF systems. This research has shown that the fertiliser response changes significantly when a crop is grown on non-trafficked soil. Fertiliser

recommendations (rate) used by the industry were not developed for CTF systems, and therefore they need to be updated to reflect the beneficial effects of improved soil structure and soil-water economy on nutrient uptake and fertiliser recovery. An additional element influencing fertiliser decision and fertiliser use efficiency is the timing of application. Timeliness (field access) is significantly improved when CTF is practised, particularly in poorly drained soils, which therefore has a positive impact on fertiliser use efficiency. Improved timeliness may enable for reduced fertiliser input, which needs to be built into the fertiliser recommendation. For no-tillage/minimum tillage systems, further work is required to optimise fertiliser placement (mainly for P and K) due to progressive nutrient stratification (e.g., Lupwayi et al., 2006; Dang et al., 2015) in these systems using previously developed techniques that minimise soil disturbance (e.g., Soane et al., 1987).

- This research also showed that the use of enhanced efficiency fertiliser formulations (e.g., ENTEC® urea) cannot be justified from the agronomic or economic perspectives if there is an underlying problem of compaction. Therefore, a recommendation is made to appropriately diagnose soil compaction-related constraints before making a decision to use relatively more expensive fertiliser formulations. Potential reductions in nitrous oxide (N_2O) emissions have been reported with these novel fertiliser formulations, but research (e.g., Tullberg et al., 2018) has also shown that soil emissions of N_2O can be up to 50% higher in non-CTF compared with CTF systems.

- The APSIM modelling approach developed by this study may be readily applied to assess potential crop productivity losses in a wider spectrum of edapho-climatic conditions. Therefore, the modelling approach reported here can be applied to simulate long-term profitability scenarios. This may be used to assist growers in the decision-making process about potential conversion to CTF by incorporating modelled productivity outcomes into whole-farm system economics.

- A recommendation has been made to explore the greater adoption of controlled traffic farming system and its implications on the grain industry and at national level. Based on my research, it is expected that because of improved fertiliser use efficiency, both profitability and environmental performance from grain production would be significantly improved if CTF had greater adoption. This research provided fundamental information, which demonstrates such benefits at the farm level. Future studies should focus on demonstrating these benefits at industry or regional scale level.

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10. APPENDICES

A. Journal Manuscripts under review/submitted

A.1. **Hussein, M A**, Antille, D., Kodur, S., Chen, G & Tullberg, JN, 'Controlled traffic farming improves nitrogen fertilizer use efficiency in wheat (*Triticum aestivum* L.): Field investigations and modelling', Submitted to the *European Journal of Agronomy*.

Controlled traffic farming improves nitrogen fertilizer use efficiency in wheat (*Triticum aestivum* L.): Field investigations and modelling

Abstract

Controlled traffic farming (CTF) is a mechanization system that confines all load-bearing wheels to permanent traffic lanes, thus optimizing productivity of non-compacted crop beds for given energy, fertilizer and water inputs. This study investigated the agronomic response and economic performance of wheat (*Triticum aestivum* L.) grown in compacted and non-compacted soils to represent the conditions of non-CTF and CTF systems, respectively. Yield-to-nitrogen (N) response relationships were derived after application of urea (46% N), urea treated with 3,4-dimethyl pyrazole phosphate (DMPP, 46% N), and urea ammonium nitrate (UAN, solution, 32%N) at rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1} N. measured soil physical and hydraulic properties were used to guide parametrization of Agricultural Production Systems Simulator (APSIM) model, which enabled long-term impacts on crop productivity to be assessed for both CTF and non-CTF, respectively. Measured results showed that grain yield, total aboveground biomass, and harvest index were 12%, 9%, and 4%, respectively higher in the CTF system compared to the crop grown under the non-CTF system ($P<0.05$). Overall, the agronomic efficiency and nitrogen recovered in grain were approximately 35% higher in CTF compared with non-CTF (≈4 vs. 3 kg kg^{-1}, respectively). Nitrogen use efficiency (NUE) was approximately 50% higher in CTF compared with non-CTF across all fertilizer types. On average, the optimal economic N application rates and corresponding grain yields were 122 kg ha^{-1} and 3337 kg ha^{-1}, and 108 and 2887 kg ha^{-1} for CTF and non-CTF systems, respectively. Modelled results showed higher water-use-efficiency and yield reduction, with up to 12% greater impact on grain yield in below-average rainfall conditions than the above average conditions, and up to 15% than the average rainfall conditions. This study demonstrated that significant improvements in fertilizer-N recoveries may not be realized with enhanced N formulations alone and that avoidance of (random) traffic compaction is a pre-requisite for improved fertilizer use efficiency.

APPENDICES

Keywords: Controlled traffic, Nitrogen use-efficiency, modelling, Soil compaction, Winter wheat.

Abbreviations: CTF, controlled traffic farming; MERN, most economic rate of nitrogen; NUE, nitrogen use efficiency; TN, total nitrogen; UAN, urea-ammonium nitrate; HI, harvest index; GM, gross margin; APSIM, Agricultural Production Systems sIMulator; DMPP, dimethyl pyrazole phosphate; TVC, total variable costs.

Introduction

This article, the first in a series of two, reports the results of field and modeling investigations into the short and long-terms effects of controlled traffic farming on wheat crop responsiveness to nitrogen fertilizers and derive the optimum N rate compared with non-controlled system. The second article (Hussein et al., submitted) deals with the agronomic and economic assessments of sorghum as affected by controlled and non-controlled traffic of farm machinery. These two articles comprise experimental and modelling data, to demonstrate the potential agronomic and economic benefits of adopting CTF in grain cropping. The dataset reported complemented by Tullberg et al., (soil and tillage research, in press) in to the potential of CTF to reduce soil emission.

The in-field traffic intensity and the size and weight of agricultural machinery, such as tractors and combines have increased in response to the agricultural specialization and the pursuit of a higher operations efficiency and capacity (Arvidsson, 2001). Adoption of heavy farm machinery significantly increase the risk of subsoil compaction with wheel loads in excess of 5 Mg (Bennett et al., 2015). Compaction induced by vehicle traffic increases soil strength, which therefore reduces water and nutrient uptake by plants due to restricted root development and penetration into the soil, and thus reduced crop yield and profitability (Taylor and Brar, 1991; Unger and Kaspar, 1994; Lipiec et al., 2003). Several studies emphasized the negative impacts of compaction on a number of key soil physical and hydraulic properties (Radford et al., 2000; Hamza and Anderson, 2005), and their impact on crop yield under dryland (Sadras et al., 2005), and irrigated cropping systems (McGarry and Chan, 1984; McGarry, 1990; Braunack et al., 1995) across a wide range of soil types and environments. In order to ameliorate, avoid or minimise soil compaction problems and reduce the subsequent risk of poor agronomic performance, the traffic of farm machinery has to be controlled (Chan et al., 2006).

Controlled traffic farming (CTF) is a mechanization system in which tramlines and crop beds are distinctly and permanently separated to optimize conditions for trafficability with farm machinery as well as soil conditions for crop growth. Much of the research tries to demonstrate how different fertilizer formulations can increase efficiency but make no reference underling effect of compaction (Halvorson et al., 2014; Halvorson and Bartolo, 2014; Gregorich et al., 2014). Recent studies (e.g., Antille et al., 2015a) have shown that CTF systems have the potential to either reduce nitrogen (N) fertilizer inputs without compromising crop yield or increase crop yield for a given fertilizer input. This is supported by studies showing enhanced structural conditions in soils established under CTF (e.g., McHugh et al., 2009) and by enhanced nutrient uptake in the absence of traffic compaction (e.g., Lipiec and

Stępniewski, 1995). However, no detailed studies have been reported on the effects of traffic compaction on the actual yield-to-fertilizer response relationships from which optimum economic N application rates could be derived. Similarly, the impacts of rainfall variability on crop productivity under different traffic systems are unknown, particularly for subtropical soil and climatic conditions.

Objectives and scope

The objectives of this study were to: (1) determine the effect of compaction induced by traffic of farm machinery on the yield-to-nitrogen response relationships, N-fertilizer use efficiency, and optimum economic application rate of different N fertilizer formulations, (2) conduct technical-economic analysis to quantify the effects of traffic-induced soil compaction on crop's gross margins and economic return as a result of changes in the price of nitrogen fertilizers and grain yield, and (3) determine the long-term impact of simulated conditions of CTF and non-CTF on the agronomic performance and water-use-efficiency using the Agriculture Production System Simulator (APSIM) model; for a dryland wheat crop grown on Red Ferrosol soils under subtropical climate condition.

To achieve this objectives, soil conditions (density) representative of controlled and non-controlled traffic systems were obtained by removing compaction through subsoiling to a depth of approximately 300mm and by performing six passes of a medium-sized tractor, respectively. Winter wheat was established and the crop subject to the fertilizer treatments has further described in the next section. Grain yield and agronomic efficiency of applied N fertilizers were determined using different methods. Field data including the data of soil properties and crop were used to guide parameterization and application of the Agricultural Production Systems Simulator (APSIM) model (Keating et al., 2003; Holzworth et al., 2014), which was subsequently used to assess the likely impact of soil compaction on crop productivity.

Materials and methods

Experimental site

The experiment was conducted at the University of Southern Queensland (27°36'35.27"S, 151°55'50.62"E) located in Toowoomba (Queensland, Australia) during the 2015 winter season. Rainfall and temperature records for the experimental site are shown in Figure 1. Total rainfall in May 2015 (138 mm) largely exceeded long-term (1970-2014) records for this month (57 mm), and it was relatively lower in June-July and October 2015, respectively. Overall, mean air temperatures did not departure significantly from long-term records, despite that minimum temperatures were slightly below average, particularly in early spring.

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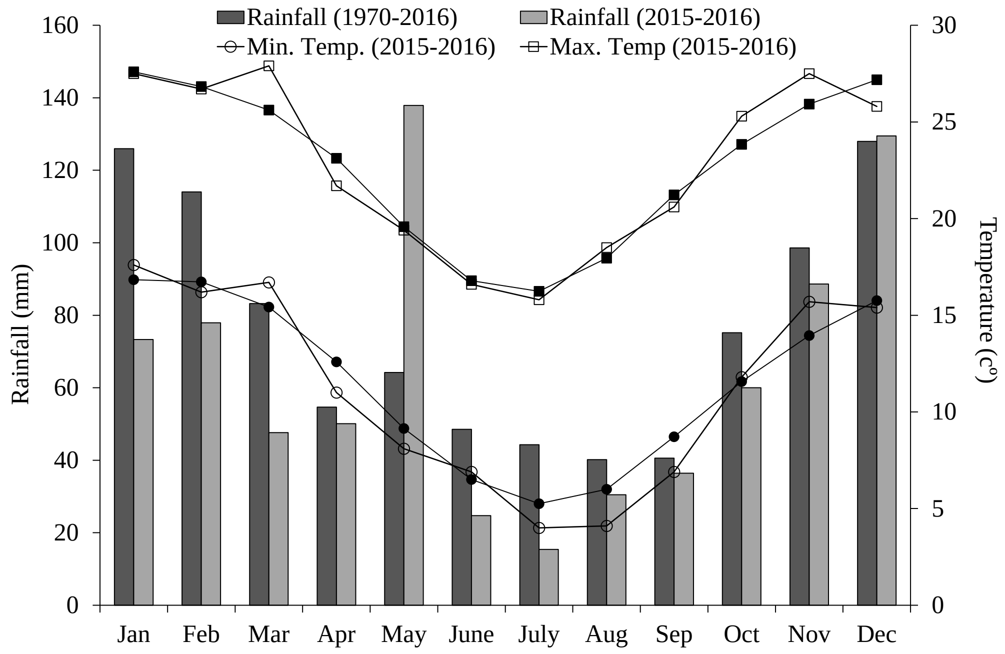

Figure 1. Monthly rainfall (mm), maximum and minimum temperatures for 2015 and long-term (1970-2000), records for Toowoomba, QLD, Australia (BOM, 2017).

The soil at the site is described in Isbell (2002) as a Red Ferrosol, which is well-drained and has a gentle slope (<0.8%), and it is similar to those frequently occurring in Queensland. Soil textural analyses (Gee and Bauder, 1986) for the bulked 0-200 mm layer were: 69% clay, 11% silt, and 20% sand. There was a requirement to remove historical compaction (300 mm depth) at the experimental site to enable the two traffic treatments (CTF and non-CTF, respectively) to be imposed (Godwin, 2011). For this, the soil was first chisel-plowed to a depth of 300 mm and this arranged based on an earlier study in SE Queensland (Antille et al., 2016), which showed that removal of compaction to such depth was sufficient to return mine-rehabilitated land affected by compaction to satisfactory crop production and that rainfall-use efficiency achieved after cultivation was ≥85% in most years. Subsequently, a power rotary harrow was used to smooth and level off the soil surface. No further tillage operations were conducted in soil representing the CTF system. The 'random', non-controlled traffic system (non-CTF) was established by imposing traffic compaction to the corresponding plots after conducting the tillage operations described above. This was performed by adjacent wheel-beside-wheel passes with a Belarus 920 tractor (100 HP, gross mass: 4 Mg) driven at a speed of 5 km h^{-1}, fitted with 11.2-20 (front) and 15.5-38 (rear) tyres inflated to 0.24 and 0.18 MPa, respectively. A total of 9 passes with the tractor were required to achieve ≈30% higher soil bulk density in the non-CTF compared with the CTF treatment. This relative difference in soil compaction was considered to be appropriate based related studies (e.g., Radford et al., 2001; Antille et al., 2013; Godwin, 2011) albeit on different soils. Mean (SD) soil moisture at the time of traffic was 18% ± 1 and 20.5% ± 0.6 (w w^{-1}) at the 0-200 mm and 200-400 mm depth intervals, respectively.

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Wheat (*Triticum aestivum* L. *c.v.* Summate) was sown on 13 June 2015 at a field-equivalent seeding rate of 60 kg ha^{-1} (Angus and Fischer, 1991), and subject to standard agronomic practice; except for the fertilizer application, which was dependent on treatment. Sowing was conducted with a 7-row conventional driller fitted with Janke press wheels and knife points at 250 mm row spacing. Phonological stages (Zadoks et al., 1974) were recorded during the crop cycle. Supplementary irrigation (≈20 mm) was applied after sowing to ensure crop establishment was satisfactory, and within the recommended timeframe for winter cereal crops in SE Queensland. A blanket fertilizer application (40 kg ha^{-1}) of Granulock® Starter Z fertilizer (11% N, 21.8% P_2O_5, 4% SO_3, and 1% ZnO) was applied to all plots at sowing based on fertilizer recommendations given in Price (2006).

The experiment was conducted in two adjacent blocks; namely: CTF and non-CTF, in which 60 plots (dimensions: 3.25-m × 5-m) with 13 plant rows per plot were laid-out in a completely randomized design, and subject to the fertilizer treatments described here. Three types of fertilizer were used: urea (46% N), urea treated with 3,4-dimethyl pyrazole phosphate (DMPP), commercially known as ENTEC® urea (46% N), and urea ammonium nitrate referred to as UAN (30% N, solution). All fertilizer treatments, including controls, were setup in triplicate (n=3). The fertilizers were hand-applied in a single band (≈50 mm) next to the plant row and incorporated at N rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1}. For all fertilizer treatments, the full N application rate was halved and the splits applied at tillering (7 August 2015) and subsequently at early stem elongation (20 August 2015), respectively.

Soil measurements and analyses

Soil bulk density (ρ_b) was determined for the 0-300 mm depth layer at regular increments of 100 mm by taking soil cores of 50 mm in diameter. Measurements were taken three times (n=3) before and after the traffic treatments were imposed, and ρ_b was determined based on Blake and Hartge (1986) (Table 1). Maximum bulk density derived from the Proctor (BSI, 1975) test was 1.70 g cm^{-3} at a derived soil moisture content of 21.2% (w w^{-1}). Total porosity of soil was derived from density properties based (McKenzie et al., 2002) using a nominal particle density of 2.65 g cm^{-3}, which was considered to be appropriate for the range of soil types investigated (Hurlbut and Klein, 1977). Soil penetration resistance was measured by pushing a cone (125 mm^2 base area, 30° apex angle) into the soil to a depth of 500 mm at constant speed (0.05 m s^{-1}), and by digitally recording the force at 25 mm depth increments based on ASABE Standard EP542 (ASABE, 2013). Gravimetric soil moisture content was simultaneously determined because of its influence on soil strength (Ayers and Perumpral, 1982). Measurements of soil moisture content and soil penetration resistance were conducted ten times (n=10). Soil water infiltration was measured using the double-ring infiltrometer method (Parr and Bertrand, 1960). Infiltration rates were subsequently obtained by differentiating Kostiakov's equation (Eq. 1) with respect to time to describe the relationship between the rate of infiltration and times (Eq. 2). Measurements were replicated three times (n=3).

$$F_t = a \times t^n \tag{1}$$

$$I_t = a \times n \times t^{n-1} \quad (2)$$

Where: F_t is cumulative infiltration (mm) at time t (h), a and n are constants, and I_t is instantaneous infiltration rate (mm h^{-1}) at time t (h).

Saturated hydraulic conductivity (K_{SAT}) of soil was measured for both CTF and non-CTF plots using the constant head test (Klute, 1965). The outflow leachate was collected in beakers at the bottom of the column. The measurements of the leachate and timing of the duration required to obtain leachate enabled K_{SAT} to be determined. The K_{SAT} for a vertical soil core under constant head is found using Eq. 3 (Hillel 2004).

$$K_{SAT} = \frac{VL}{AHt} \quad (3)$$

Where: V is the volume of solution (mm^3), L is the length of the soil core (mm), A is the area of the soil core (mm^2), H is the water head from base of core to top of solution (mm), and t is the time for V to flow through (h).

Drained upper limit (DUL) is the highest field-measured water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible, and DUL is referred to as field capacity. This parameter was measured based on the approach used by Ratliff et al., (1983). Soil $pH_{1:5}$ and electrical conductivity ($EC_{1:5}$) were 6.22 and 0.07 ds m^{-1}, respectively (Rayment and Lyons, 2011).

Crop measurements and analyses

The crop was harvested by hand-cutting the entire plant from two-linear meters of the two central rows of each plot at approximately 20 mm above the soil surface on 11 November 2015. These samples were used to determine grain yield, expressed as kg ha^{-1} at 14% (w w^{-1}) moisture content, and the following yield components: harvest index (HI), the ratio grain weight-total aboveground biomass (Donald and Humblin, 1976); thousand grain weight (TGW) (MAFF, 1986, Method No.: 73), number of grains per ear, and ears per square meter (ears m^{-2}). Cumulative dry matter was also determined at major phonological stages (Zadoks et al., 1974) from one-linear meter samples per plot collected from the second crop row from the edge of the plot. Total N in grain (MAFF, 1986, Method No.: 48) was used to estimate apparent N recovery in grain by the difference method, and to estimate nitrogen use efficiency (NUE). Differences in yield between fertilized and non-fertilized crops, relative to N applied as fertilizer, were used to denote agronomic efficiency (AE), which was determined for all four crops. These relationships are shown in Eq. [4] and [5], respectively (after Baligar et al., 2001):

$$NUE\ (\%) = \frac{(U_F - U_{F=0})}{N_{Rate}} \quad (4)$$

$$AE\ (\text{kg}\ kg^{-1}) = \frac{(Y_F - Y_{F=0})}{N_{Rate}} \quad (5)$$

Where: NUE is nitrogen use efficiency (%) based on apparent N recovery in grain U_F and $U_{F=0}$ are N recoveries in grain (kg ha^{-1} N) from fertilized- and non-fertilized (control) crops, respectively, and N_{RATE} is N application rate (kg ha^{-1}). AE is agronomic efficiency (kg kg^{-1}), Y_F and $Y_{F=0}$ are grain yields (kg ha^{-1}) corresponding to fertilized- and non-fertilized (control) crops, respectively.

Yield-to-nitrogen response relationships were examined by applying nonlinear regression analyses, and by fitting quadratic functions to the data (Abraham and Rao, 1966). The approach used in this work is from studies (e.g., Kachanoski, 2009; Antille et al., 2017) dealing with cereal crop responses to applied N fertilizer, and assumes a quadratic-plateau relationship. Crop's gross margin (GM) was estimated as the difference between gross income (GI) and total variable costs (TVC). This analysis uses the optimum N application rate (MERN), derived from the yield-to-nitrogen response relationships, and price ratio (P_R), which is defined as the price of the nitrogen fertilizer (P_N) divided by the price of the crop (C_P) (Kachanoski et al., 1996). Estimate the fertilizer component of the variable costs and also to derive the corresponding grain yield from the yield-to-nitrogen response curve (Galambošová et al., 2017). Therefore, GM reflects the gross profitability of the crop when fertilizer N input is optimized.

A simplification was made by assuming that variable costs were identical in both traffic systems; except for the fertilizer costs, which were dependent on fertilizer treatment. In well-design CTF systems in Australia, the area subject to traffic typically occupies 15% (or less) of the cultivated field area, particularly when permanent no-tillage is practiced. By contrast, where CTF is not practiced, this area is often greater than 65% when shallow tillage is practiced and 45% when no-tillage is practiced, and it can be as high as 85% in conventional tillage systems that require primary tillage operations prior to crop establishment (Kroulík et al., 2009). In Australia both tillage systems are using, which therefore GM calculations were adjusted to reflect the effect on yield of the relative areas affected by traffic compaction in typical CTF and non-CTF systems, respectively. For shallow tillage, it was assumed that 65% and 35% of the cultivated area in the non-CTF system was and was not subject to traffic compaction, respectively. While when zero-tillage (ZT) is practiced, it was assumed that 45% and 55% of the cultivated area in the non-CTF system was and was not subject to traffic compaction, respectively. For the CTF system, these relative areas were 15% and 85%, respectively. Hence, the corresponding GI for each traffic system was derived by adjusting Y_{MERN} in Equations (Eq. 6), (Eq. 7) and (Eq. 8) by these relative percentages, respectively. This was considered to be a fair assumption based on earlier studies (e.g., Galambošová et al., 2017).

$$Y_{MERN}(non-CTF) = [(Y_{MERN}(CTF) \times 0.35) + (Y_{MERN}(non-CTF) \times 0.65)] \quad (Shallow\ tillage) \qquad (6)$$

$$Y_{MERN}(non-CTF) = [(Y_{MERN}(CTF) \times 0.55) + (Y_{MERN}(non-CTF) \times 0.45)] \quad (Zero-tillage) \qquad (7)$$

$$Y_{MERN}(CTF) = [(Y_{MERN}(CTF) \times 0.85) + (Y_{MERN}(non-CTF) \times 0.15)] \qquad (8)$$

Where: Y_{MERN} is crop yield correspondent to MERN (kg ha^{-1}); CTF and non-CTF are controlled and non-controlled traffic farming systems, 0.65 and 0.35 are the relative areas that was and was not subject to traffic compaction, respectively, under non-CTF system when 'shallow tillage' is practiced; 0.45 and 0.55 are the relative areas that was and was not subject to traffic compaction, respectively, under non-

CTF system when 'zero tillage' is practiced; 0.15 and 0.85 are the relative areas that was and was not subject to traffic compaction, respectively, under CTF system. This assumption is considered to be an appropriate as ZT is practiced by most growers who have converted to CTF system (Tullberg, 2007), with some exceptions (Dang et al., 2017).

Modeling of crop performance

Simulations were conducted using the Agriculture Production System Simulator (APSIM) farming systems model (Holzworth et al., 2014). Full documentation for APSIM's modules, mathematical structure and source codes can be found at www.apsim.info/documentation/. Simulations involved dryland wheat crop, grown under both CTF and non-CTF systems on a Red Ferrosol soil, and were conducted on a continuous basis for 56 years (1960 to 2015). Climate data was obtained from the Australian Bureau of Meteorology weather station (41529) at Toowoomba via patched point data set (Jeffrey et al., 2001). A process modelling approach was chosen to quantify the likely impact of soil compaction on crop phenology, as described previously (Antille et al., 2016) except that SoilWat module was used to represent the soil water processes instead of SWIM module (Huth et al., 2012).

Measured soil data was used to represent drained upper limit (DUL) and saturated water content (SAT), and bulk density (BD) for CTF and non-CTF conditions to a depth of 300 mm, except for saturated hydraulic conductivity (K_{SAT}) which was measured to a depth of 150 mm. The BD data for 300-1800 mm depth and K_{SAT} for 150-1800 mm depth for CTF condition were derived and modified from measured data on similar Red Ferrosol soil (Dalgliesh and Foale, 1998; Connolly et al., 2001). Pedotransfer functions were fitted for CTF condition to estimate lower limit (LL) water content for all soil depths (0 to 1800 mm), and DUL and SAT water contents for the deeper depths (300 to 1800 mm) interval, using particle size analysis data derived via the Pipet method (Gee and Bauder, 1986). For non-CTF conditions, these data were obtained from field data (soil physical and hydraulic properties) and a series of assumptions as described earlier (Antille et al., 2016). A runoff curve number (that is runoff as a function of total daily rainfall), which describes runoff potential for bare-soil, was set at 73 units for CTF (Kodur et al., 2014); and was increased by 7 units for non-CTF conditions based on an earlier study by Owens et al., (2016). Default soil evaporation parameters were set according to Kodur (2017). The default parameters are the one that comes as a default with the APSOIL database. Soil properties and input parameters used in the model are presented in Table 2.

Wheat (*Triticum aestivum* L. *c.v.* Summate) was sown every year on defined sowing rainfall (at least 20 mm over a 5-day period) between 15th May and 15th July. If the defined rainfall did not occur, the model was forced to sow a crop on 31st July so that cropping can occur every year. Wheat was sown at 100 plants m^{-2} and received a N application rate of 110 kg N ha^{-1}, which corresponded with the optimum N application rate in the form of urea (Table 2). Nitrogen was applied 30 days after of sowing consistent with standard agronomic practice, which is based on the stage of the crop (Zadoks et al., 1974). Initial moisture in the first year of study was 95% of maximum soil available water capacity and was obtained by prior running the model for 10 years. The APSIM-Wheat module within APSIM has been broadly tested across soil and climate conditions in Australia and internationally, for a range of experimental conditions (e.g., Carberry et al., 2013; Holzworth et al., 2014). However, to further represent the conditions of the current field study, the simulated yield data for both CTF and non-CTF conditions were calibrated, and validated against the field data. The difference in yield between CTF and non-CTF conditions under modelled conditions (13%) was similar to those observed under field (12%). Water-use-efficiency is defined in this study as the ratio of grain yield (kg ha-1) to total rainfall that received during the corresponding season (Hochman et al., 2009).

Table 1. Bulk density (BD), plant lower limit (LL), drained upper limit (DUL), saturation (SAT), and saturated hydraulic conductivity (K_{SAT}) used in the simulations† for CTF and non-CTF conditions for a Red Ferrosol soil at Toowoomba, QLD, Australia. The standard deviation (SD) is shown for measured values as ± the mean value (*n* = 3), except when not shown (*n* = 1).

Depth (mm)	BD (g cm^{-3})	Total porosity (%)	Plant LL (m^3 m^{-3})	DUL (m^3 m^{-3})	SAT (m^3 m^{-3})	K_{SAT} (mm day^{-1})
CTF						
0-150	1.15±0.04	57±0.01	0.21	0.31±<0.01	0.55	1000±6.65
150-300	1.17±0.02	56±0.02	0.24	0.31±<0.01	0.54	500
300-600	1.20	55	0.22	0.36	0.48	100
600-900	1.20	55	0.24	0.35	0.44	50
900-1200	1.22	54	0.25	0.36	0.43	50
1200-1500	1.25	53	0.25	0.33	0.40	25
1500-1800	1.30	51	0.27	0.33	0.40	25
non-CTF						
0-150	1.34±0.04	49±0.01	0.22	0.26±<0.01	0.48	50±0.08
150-300	1.27±0.03	52±0.01	0.25	0.28±<0.01	0.49	25
300-600	1.30	51	0.24	0.37	0.44	10
600-900	1.28	52	0.25	0.35	0.41	25
900-1200	1.28	52	0.26	0.36	0.41	25
1200-1500	1.27	52	0.25	0.33	0.39	25
1500-1800	1.32	50	0.27	0.33	0.39	25

† Data for BD, DUL, SAT and K_S data for 0 to 300 mm depth were directly measured in the field, data for 300-1800 mm depth were derived using Pedotransfer functions (DUL and LL from particle size analysis; K_{SAT} 150-1800 mm was based on adjustments using Red Ferrosol soil data by Connolly et al. (2001) and APSOIL database (Dalgliesh and Foale, 1998). Data for non-CTF conditions were adjusted based on field conditions, as explained (Antille et al., 2016b).

Statistical analyses

Statistical analyses for crop and soil data used Statistical Package for the Social Sciences (SPSS-version 23) software (Swan and Sandilands 1995). Means of cone index were compared for significance using LSD at 5% level of probability, and using Duncan for the rest of means data at the same level of probability. Statistical analyses were graphically assessed by means of residual plots and normalization of data was not required. Yield-to-nitrogen responses were investigated by means of nonlinear (quadratic) regression analyses. Linear regression analyses were also applied to examine the relationships between grain yield and N application rates. Nonlinear regression analyses were used to describe the relationships between nitrogen-use-efficiency and N application rates, from which nitrogen-use-efficiency and agronomic efficiency corresponding to most economic rate of nitrogen were derived. Analytical values are reported as the mean ± standard deviation (SD).

Results

Soil physical and hydraulic properties

Soil penetration resistance determined for traffic treatments representing CTF and non-CTF systems is shown in Figure 2. Overall, there were significant differences ($P<0.05$) in soil cone index between the two traffic systems, particularly in the 50 to 300 mm depth interval, where penetration resistance was up to 40% higher in non-CTF. Mean values of cone index in the 0-500 mm depth range were 2.56 and 4.32 MPa (LSD 5% level: 1.32) for the CTF and non-CTF systems, respectively. No differences in penetration resistance were observed below 350 mm deep, which therefore reflects historical soil compaction not removed by tillage. Differences in cone index found between wheeled and non-wheeled soil were consistent with the differences in bulk density (1.15 g cm^{-3} in the 0-150 mm depth) and absence (1.35 g cm^{-3} in the 0-150 mm depth) of wheel traffic (Table 1). Differences in soil moisture content between the two traffic systems were small ($P>0.05$).

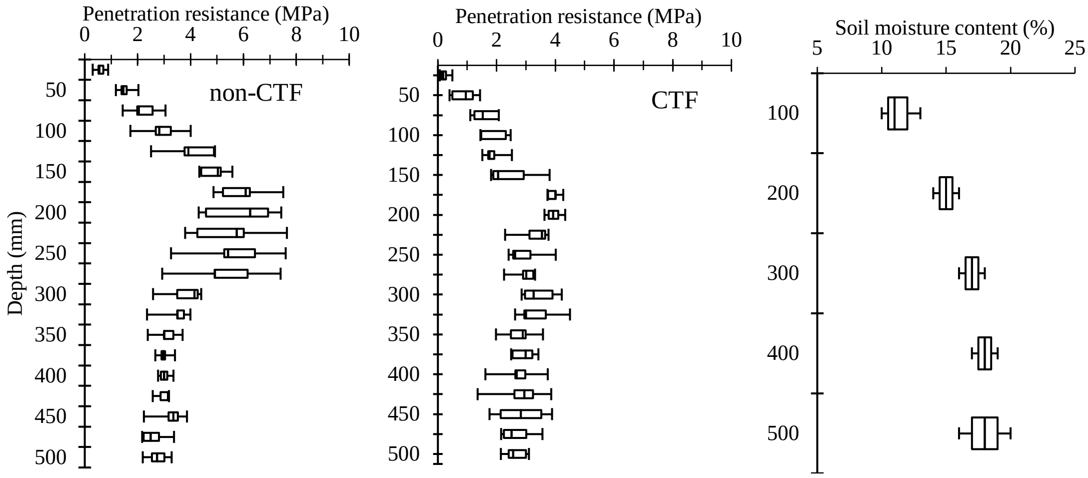


Figure 2. Soil penetration resistance and soil moisture content observed at the experimental sites for the CTF and non-CTF systems. For penetration resistance use $P<0.05$ for cone index, and $P>0.05$ for soil moisture content. Box plots show Min, Q_1, Med, Q_3, and Max, respectively. Use n = 10 for cone index and moisture content.

Soil water infiltration rates for the CTF and non-CTF are shown in Figure 3. Infiltration rates were significantly lower in non-CTF compared with CTF at any given time (P-values <0.05). Infiltration rates in CTF were approximately double those of the non-CTF system at any given time (mean values of 3.0 and 1.50 mm $min.^{-1}$ for CTF and non-CTF), respectively. These results are consistent with measurements of saturated hydraulic conductivity (K_{SAT}) reported in Table 1, which were 20 times higher ($P < 0.05$) in CTF compared with non-CTF (e.g., 1000 mm day^{-1} vs. 50 mm day^{-1}, respectively).

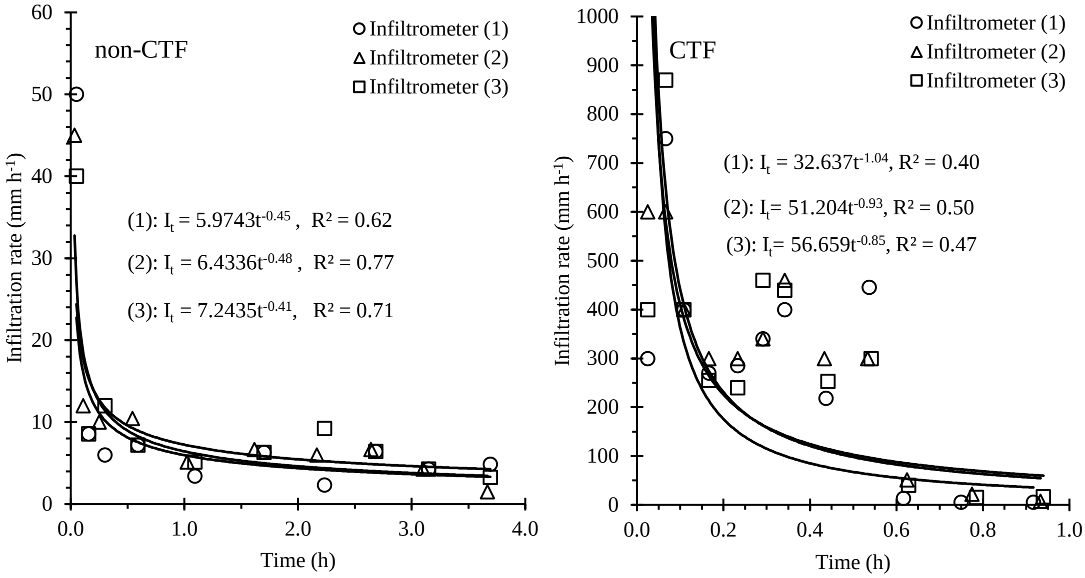


Figure 3. Relationship between infiltration rate (I_t, mm h^{-1}) and time (t, h) recorded at the experimental site for the two traffic treatments. Use P<0.05.

Grain yield and yield components

There were significant differences in grain yield between CTF and non-CTF as well as between fertilizer-treated crop and controls (zero-N), which were observed in both traffic systems (P-values <0.05) (Figure 4). Comparisons between non-fertilized crops showed that grain yield was approximately 250 kg ha^{-1} higher in CTF compared with non-CTF ($P < 0.05$). For fertilizer-treated crop, grain yield was approximately 400 kg ha^{-1} (≈12%) higher in CTF compared with non-CTF. The optimum nitrogen application rates (MERN), and corresponding grain yields, were 122 and 3336 kg ha^{-1}, and 108 and 2887 kg ha^{-1} for CTF and non-CTF, respectively. Overall, there was not fertilizer type effect on grain yield, which suggested that compaction was the main factor influencing the response to applied N fertilizer. Thus, grain yield was relatively more sensitive to soil compaction than fertilizer N formulation. This effect was consistent at any given rate of nitrogen fertilizer. There was not fertilizer type × N application rate effect on grain yield, which was observed in both traffic treatments (P>0.05).

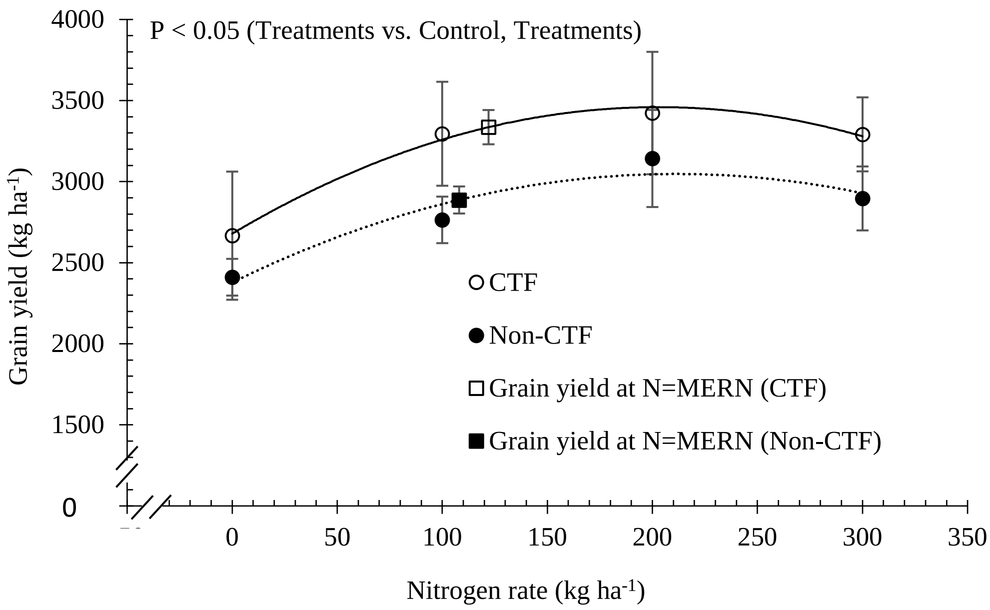


Figure 4. The relationship between N application rates and grain yield as affected by traffic of farm machinery. Error bars denote standard deviation (SD) of mean (n = 9, except for N=0 and N=MERN, n = 3).

Thousand grain weight (TGW), number of spikes and number of grains per m^2 showed significant differences between soil conditions (P-values<0.05), and therefore were consistent with grain yield results (Figure 5). Difference in TGW between CTF's control (43.3 ± 0.76 g) and non-CTF's control (42 ± 0.55 g) was also significant (P<0.05). There were significant differences in aboveground biomass between fertilizer-treated crop and controls, which were observed in both traffic treatments (P<0.05), but there was not fertilizer type effect on aboveground biomass (P>0.05). Overall, cumulative aboveground biomass was higher in CTF compared with non-CTF, which also reflected enhanced response to applied fertilizer-N in the absence of traffic compaction (Figure 6). Traffic treatment effects on aboveground biomass were significant after tillering, which also explained difference in dry matter accumulation throughout the crop cycle and dry matter partitioning. There was a nitrogen rate effect (P<0.10) on cumulative aboveground biomass, which was only observed after flag leaf.

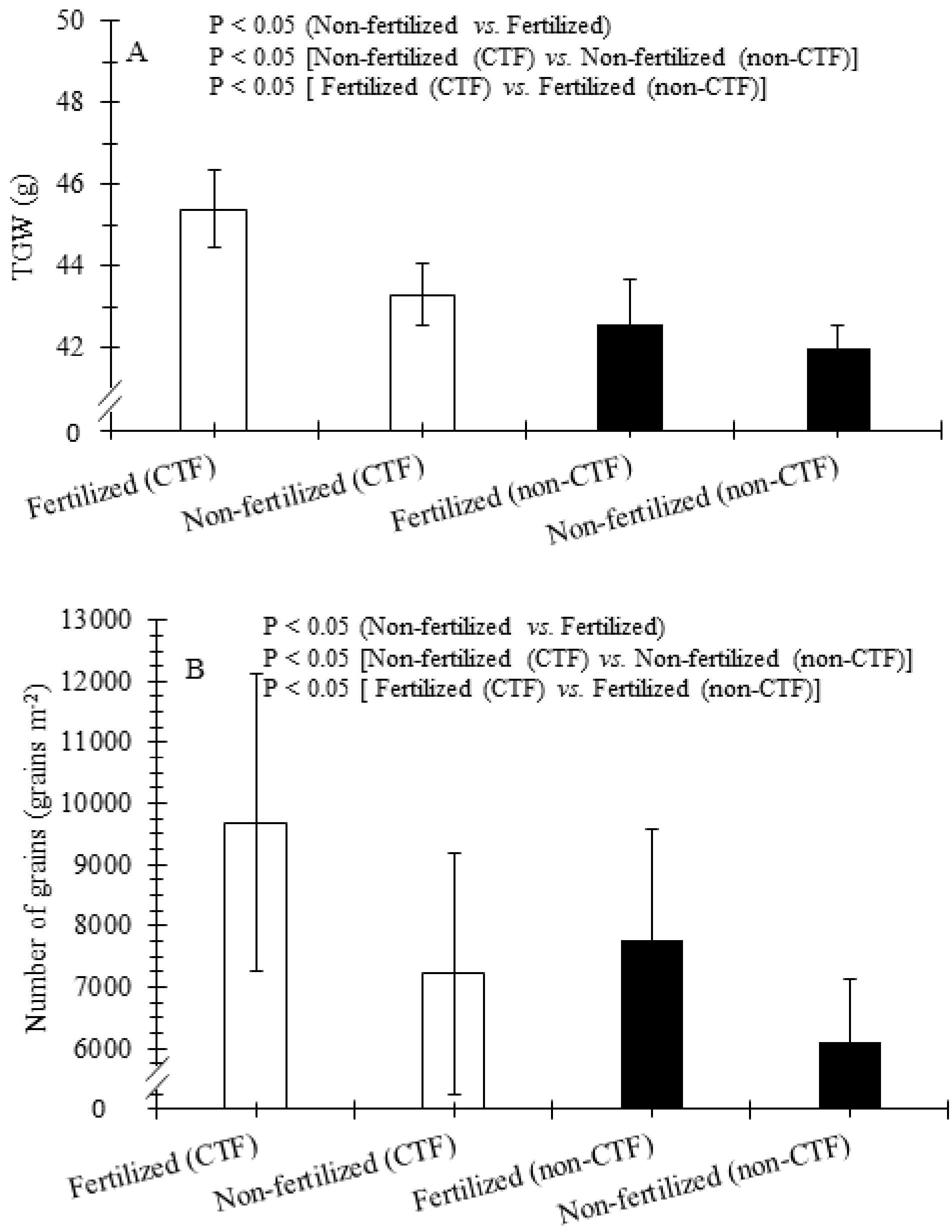


Figure 5. (A) Thousand grain weight (TGW), and (B) number of grains per m^2 as affected by traffic of farm machinery. Error bars denote standard deviation (SD) of mean [n = 27 (fertilized), except for N=0 (non-fertilized), n = 3].

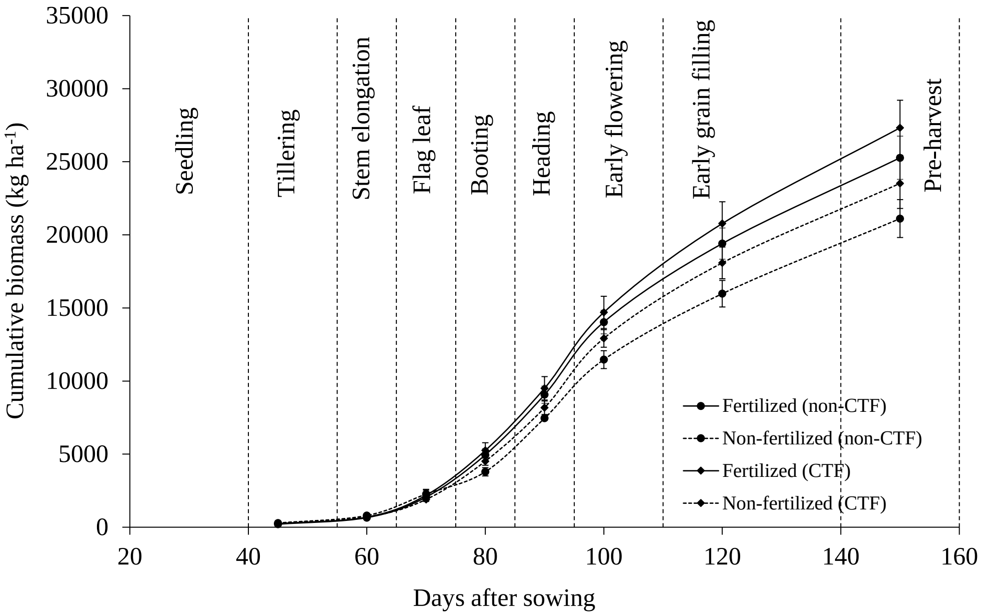


Figure 6. The effect of traffic compaction on cumulative aboveground biomass of wheat. Error bars denote standard deviation of the mean. Crop growth stages are based on Zadoks et al. (1974). Use n = 27 for treatments and n = 3 for controls).

Differences in harvest index were generally small (≤4%) and not affected by traffic treatment, fertilizer type or nitrogen application rate (P-values >0.05), and therefore consistent with relative changes in grain yield and total aboveground biomass (Figure 7). Harvest indices were higher when fertilizer applied at rates of 100 and 200 kg ha^{-1} N, which was in accord with estimates of optimum N application rates.

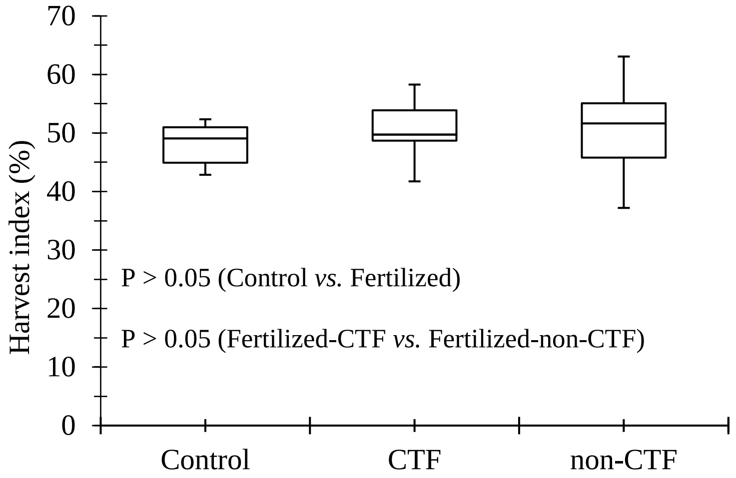


Figure 7. Harvest index as affected by CTF and non-CTF. Box plots show Min, Q_1, Med, Q_3, and Max, respectively. Use n = 6 for control (N = 0), and n = 27 for traffic-fertilized (N ≠ 0).

Nitrogen uptake and nitrogen fertilizer use efficiency

Total grain-N was significantly higher in CTF compared with non-CTF (P<0.05). Overall differences in TN between traffic treatments were approximately 6%. Nitrogen contents were approximately 10% lower in controls compared with fertilizer treatments. These differences were consistent with N recoveries in grain, which showed up to 20% increase in NUE in CTF compared with non-CTF (Figure 8).

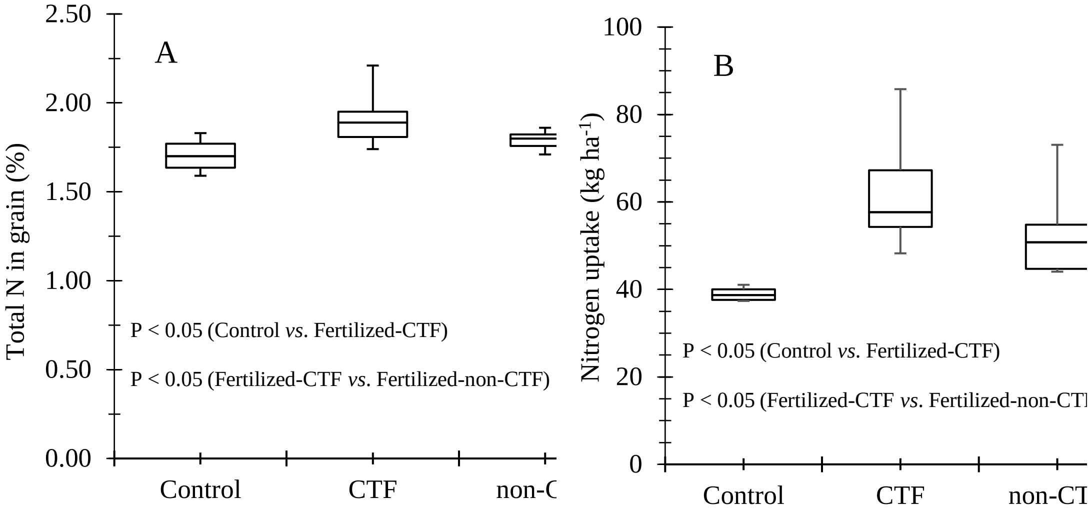


Figure 8. Traffic treatment effects on total N in grains (A), and N uptake in grain (B). Box plots show: Min, Q1, Med, Q3, and Max, respectively. Use n = 6 for control (N = 0), and n = 27 for traffic-fertilized (N ≠ 0).

The CTF system showed that nitrogen-use-efficiency (NUE) may be increased by up to 50% compared to non-CTF, which was significant (P<0.01) as shown in Figure 9. The fertilizer type effect was not significant (P>0.05) and confirmed a significantly greater effect of compaction on NUE. This also suggested that significant improvements in NUE may not be possible if changes in fertilizer formulations are not concurrent with improved soil structural conditions. The value of NUE that corresponds with the optimum N application rate was derived from the nitrogen-use-efficiency to nitrogen application rate response relationships shown in Figure 9. This shows that if N was to be applied at the optimum rate, NUE is expected to be approximately 60% higher in CTF compared with non-CTF.

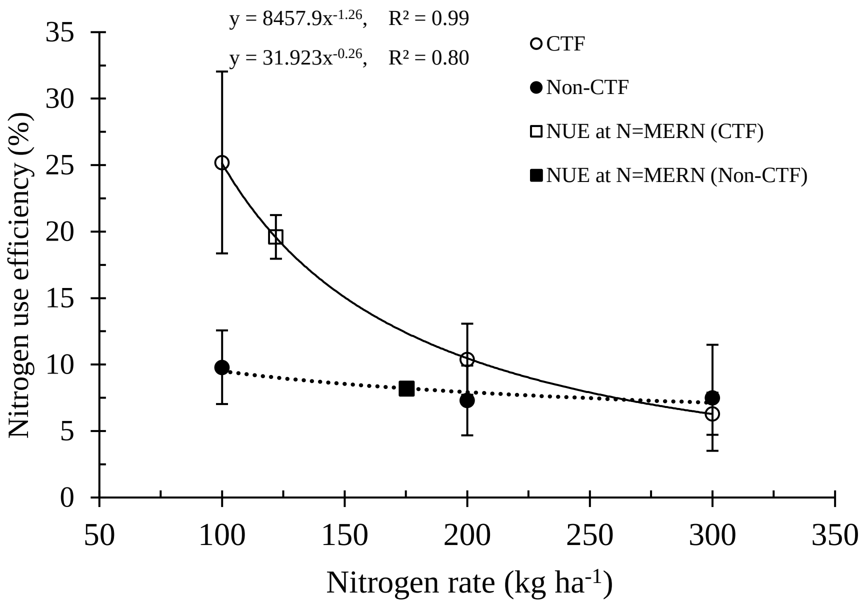


Figure 9. The relationship between N application rate and N use efficiency (NUE) for CTF and non-CTF. Error bars denote Std. of mean (n=6, except n = 3 for N = 300 kg ha-1 and N=MERN). Use P<0.05.

Overall, agronomic efficiency (AE) was ≈35% higher in CTF compared with non-CTF (≈4 vs. 3 kg kg^{-1}, respectively), as shown in Figure 10. However, at the optimum N rate (MERN), the agronomic efficiency was approximately 50% higher in CTF compared with non-CTF ($P<0.01$). Similarly, there was no fertilizer type effect on AE, which was therefore consistent with NUE calculations and also suggested a stronger compaction than fertilizer formulation effect on grain yield.

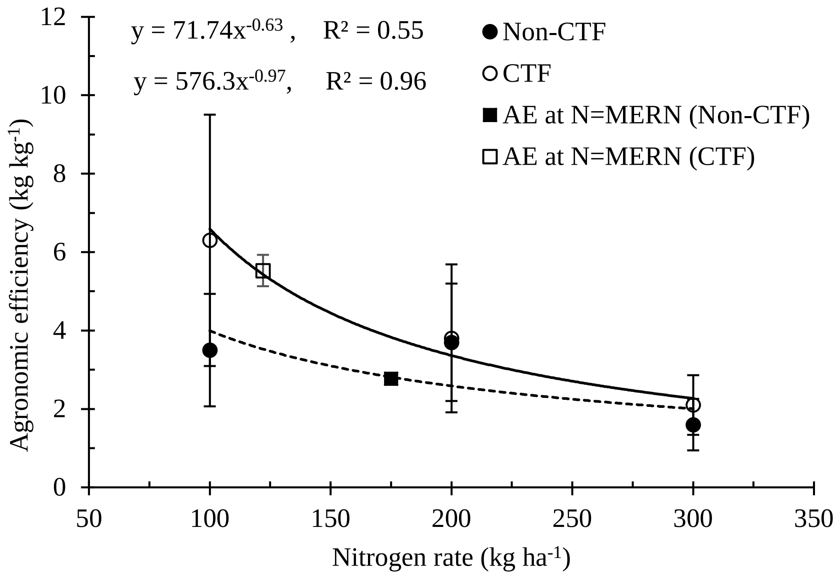


Figure 10. The relationship between N application rate and agronomic efficiency (AE) for CTF and non-CTF. Error bars denote Std. of mean (n=9, except n = 3 for N = MERN). Use P<0.05.

Most economic rate of nitrogen and gross margin analysis

Table 2 shows the most economic rate of N (MERN) and corresponding yield (Y_{MERN}) derived from the yield-to-nitrogen response relationships, and price ratios (P_R) for the year of harvest. With the exception of ENTEC under CTF, yield-to-nitrogen responses were not significant when a quadratic model was fitted to the data, which was observed in both traffic systems ($P > 0.05$). Despite this, responses were significant at a 10% probability level in non-CTF × urea, and CTF × UAN. Yield-to-N responses relationships were also tested using linear function, and the responses were not significant for both traffic systems and the three fertilizer materials ($P > 0.05$), with the exception of the CTF × ENTEC (Yield = 2742 + 2.7 N_{Rate}, $R^2 = 0.93$, P = 0.033, SE = 113), and non-CTF × urea (Yield = 2483 + 2.2 N_{Rate}, $R^2 = 0.92$, P = 0.037, SE = 93) Table 4.

Constant costs are including the costs of seed (seed, seed treatment); operations (fuel and oil, repairs and maintenance); and agro-chemical, which were equivalent to AUD 144.45 ha^{-1}. Average gross margin (GM) calculations were approximately 8% higher in CTF compared with non-CTF, if shallow tillage is practiced, and about 4% higher if zero-tillage is practiced ($P > 0.05$). Differences in gross margins between fertilizers type were mainly due to differences in the cost of N, particularly for ENTEC (indicated AUD 0.96 kg^{-1}). The impact of fertilizer-N cost on gross margin was therefore higher for the non-CTF system because of overall lower yield.

APPENDICES

Table 2. Economic rate of nitrogen (N_{MERN}) in wheat and the theoretical application rate for maximum yield response (N_{MAX}) for CTF and non-CTF systems, where price of grain (P_{Grain}); price of nitrogen (P_N); price ratio (P_R); standard error (SE); maximum nitrogen (N_{MAX}); maximum yield (Y_{MAX}); most economic rate of nitrogen (MERN); crop yield at MERN (Y_{MERN}). The standard deviation (SD) is shown as ± the mean value, use n = 12.

Treatments		P_{Grain}	P_N	P_R	Response	P-value	SE	R^2-value	N_{MERN}	Y_{MERN} (SD)	N_{MAX}	Y_{MAX}
		(AUD kg^{-1})		- -	- - -	- - -	- - -	- - -	(kg ha^{-1})			
non-CTF	UAN	0.28	0.77	2.8	$y = 2340 + 9.1x - 0.04x^2$	0.45	312	0.79	124	3079 (394)	178	3153
	ENTEC	0.28	0.96	3.4	$y = 2373 + 5.9x - 0.01x^2$	0.32	166	0.90	93	2804 (307)	224	3028
	Urea	0.28	0.75	2.7	$y = 2419 + 4.0x - 0.01x^2$	0.08	42	0.98	107	2778 (286)	320	3061
CTF	UAN	0.28	0.77	2.8	$y = 2682 + 9.2x - 0.02x^2$	0.09	65	0.99	143	3538 (412)	204	3622
	ENTEC	0.28	0.96	3.4	$y = 2662 + 5.1x - 0.01x^2$	0.03	20	0.99	106	3117 (366)	321	3485
	Urea	0.28	0.75	2.7	$y = 2693 + 8.7x - 0.03x^2$	0.20	116	0.95	117	3358 (539)	168	3427

UAN = Urea ammonium nitrate (solution, 32%N),

ENTEC = urea treated with 3,4-dimethyl pyrazole phosphate (DMPP, 46% N), and

Urea (46% N)

Table 3. Gross income (GI), total variable cost (TVC), and gross margin (GM) obtained from winter wheat based on the MERN and Y_{MERN} presented in Table 2. Constant cost is AUD 144.45 ha^{-1}. Use AUD1 ≈ USD 0.75.

Treatments		GI (AUD ha^{-1})		Fertilizer Cost	TVC	GM (AUD ha^{-1})	
		ZT[1] (45%)	ST[2] (65%)	AUD ha^{-1}	AUD ha^{-1}	ZT[1] (45%)	ST[2] (65%)
non-CTF	UAN	933	907	137	281	652	626
	ENTEC	833	815	131	275	558	540
	Urea	867	834	121	265	602	569
CTF	UAN	971		151	295	676	
	ENTEC	860		142	286	574	
	Urea	916		128	272	644	

[1] ZT when zero-tillage is practiced; and [2] when shallow tillage is practiced.

Modeling of crop performance

Modeled yield and water-use-efficiency (WUE) under rainfall variability for CTF and non-CTF conditions are shown in Figure 11. Soil compaction in non-CTF reduced in grain yield and WUE, by 13%, and 15%, respectively. While these reductions were prominent across the rainfall conditions, the yield reduction was 12% greater during below average rainfall conditions (<30th percentile; Figure 11 a; average rainfall = 191 mm/season) than those of above average conditions (>70th percentile; average rain = 330 mm/season) (Figure 11 a). Despite the differences in WUE between the two traffic systems were decreased in the years that received above average rainfall, WUE were approximately 25% and 20% greater in CTF and non-CTF, respectively, in the drier conditions compared with the wetter years (Figure 11 b).

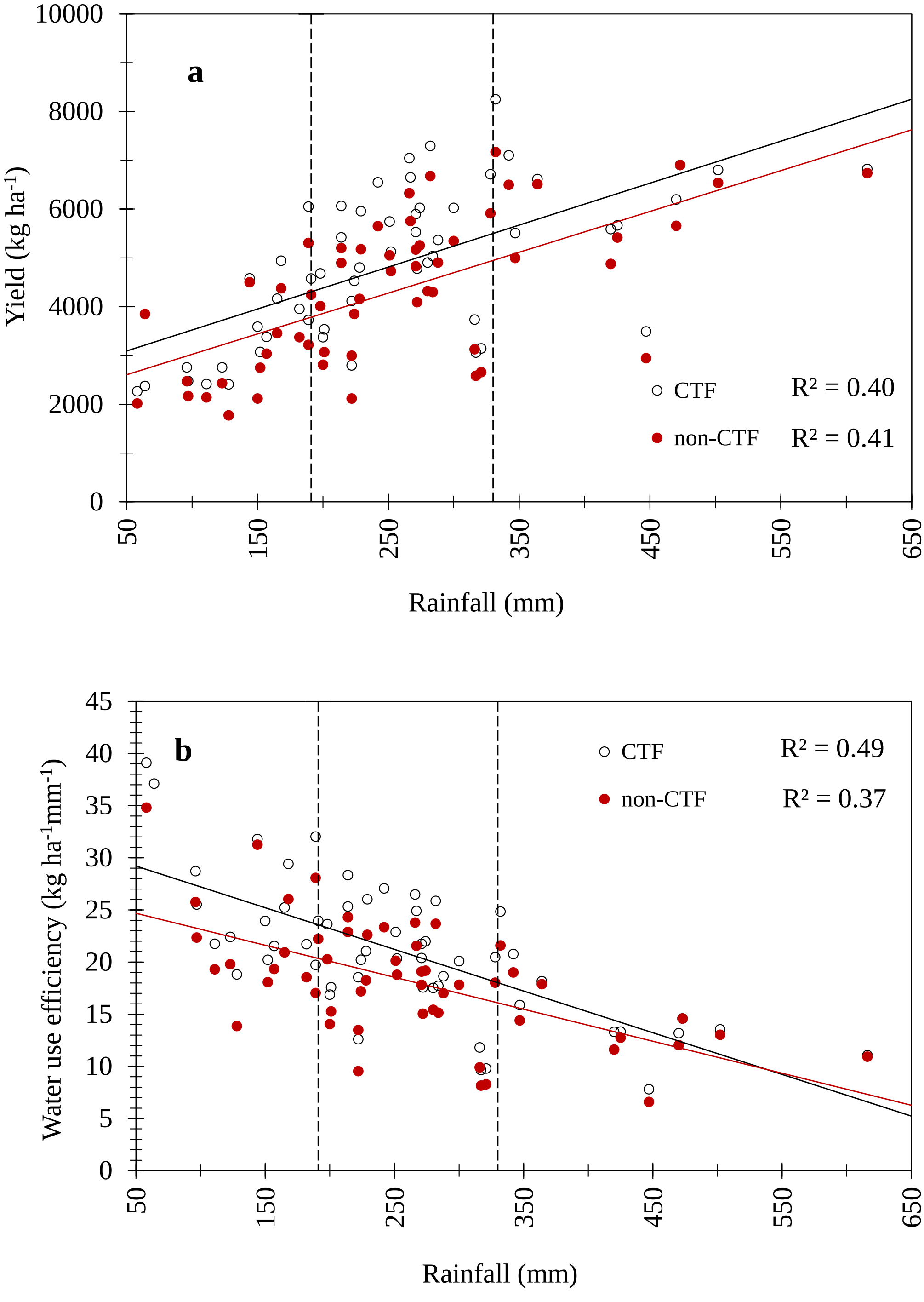
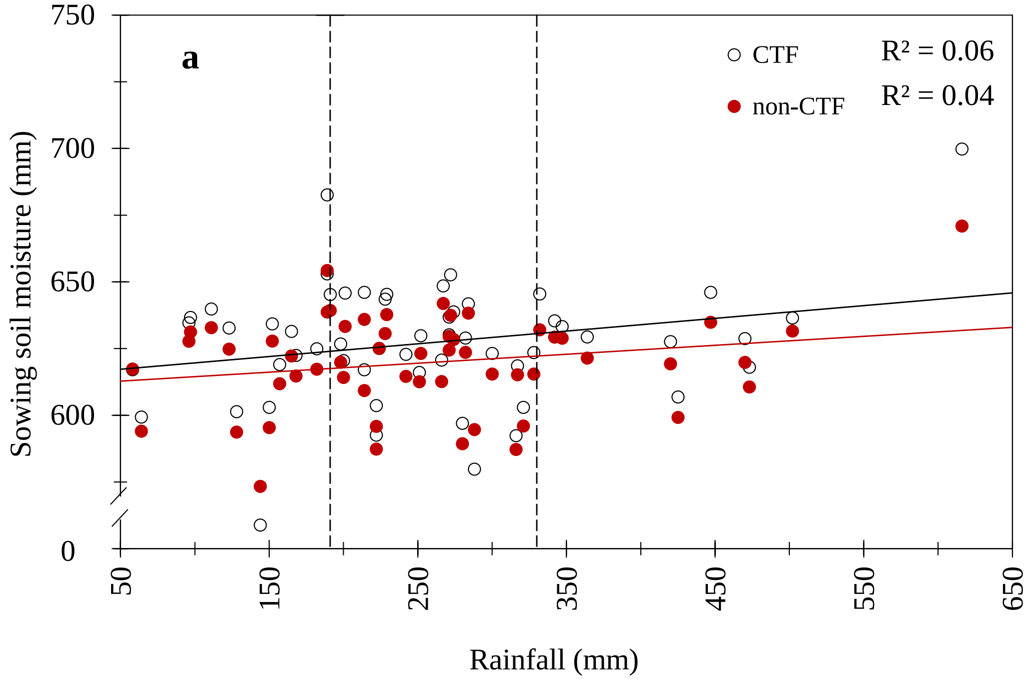


Figure 11. Yield (a), and WUE (b) for 56 years of simulated wheat-fallow cropping system on a Red Ferrosol soil at Toowoomba, Queensland for CTF (hollow circle), and non-CTF (red circle). Continuous lines show linear fit. Dotted vertical lines show 30th (left) and 70th (right) percentile rainfall.



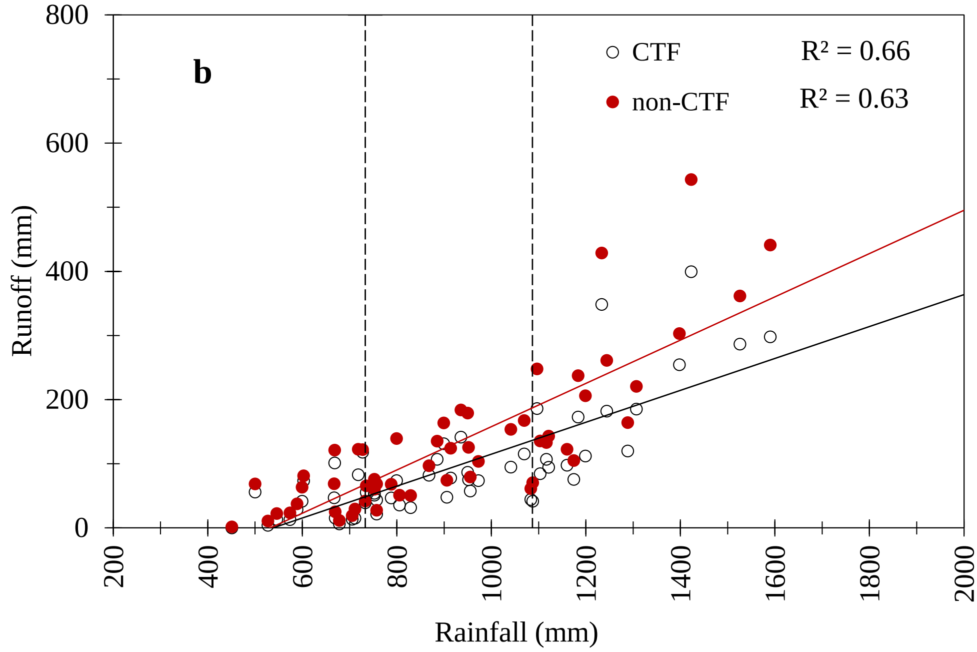


Figure 12. Sowing soil moisture (a) and runoff (b) for 56 years of simulated wheat-fallow cropping system on a Red Ferrosol at Toowoomba, Queensland for CTF (hollow circle) and non-CTF (black circle) systems. Continuous lines show linear fit. Dotted vertical lines show 30th (left) and 70th (right) percentile rainfall.

The negative effects associated with soil compaction on sowing soil moisture and runoff is shown in Figure 12. On average (56-year mean), soil compaction caused 7% reduction in sowing soil moisture, but 38% increase in runoff compared with that from CTF soil. In contrast to yield and biomass, sowing soil moisture and runoff were each increased with rainfall. That is, during above average rainfall conditions, soil compaction caused 6 mm (1%) greater reduction on sowing moisture (Figure 12 a) and a 196 mm (16%) greater increase in the runoff (Figure 12 b) than that did under CTF.

Discussion

Effect of soil compaction on soil

The ability of CTF to store more water, was attributed to the greater infiltration rate (approximately double those of the non-CTF), and hydraulic conductivity (20 times higher in CTF compared to non-CTF). These results are consistent with observations reported in earlier work by Antille et al., (2016), which indicated that hydraulic conductivity was up to ten times higher in non-trafficked soil compared with trafficked soil. The ability of CTF to holding water was also emphasized by the data of modelled runoff, which was 45% higher in non-CTF system, particularly in the wetter years (>70th percentile; average rain = 330 mm/season). This attributed to the smaller size of pores and fewer natural channel in a compacted soils, which represented by non-CTF system (Fleige and Horn, 2000). Soil cone index was consistent with the soil bulk density, however, cone index samples were collected at moisture contents ranged 10-16% (w w^{-1}), which were below the optimum moisture content (21.2%) based on the Proctor test. Therefore, the cone indices were too high compared to the bulk densities. The other reason for the high cone index was suggested by Daddow and Warrington (1983), who reported that soils with a large amount of fine particles (silt and clay) will have smaller pore diameters and a higher penetration resistance at a lower bulk density than a soil with a large amount of coarse particles. Soil compaction is increasing soil bulk density and soil penetrometer resistance and decreasing soil water infiltration are signs of soil compaction (Horn et al. 1995; Hamza and Anderson 2003, 2005); which therefore, interactions of these three factors are important for crops to influence their yield and input use efficiency (Marshall and Tokunaga 2006).

Effect of soil compaction on grain yield and yield components

Field Measurements

The grain yield is usually affected by two main components, which are number and weight of grains (Slafer, 2003). These two components are affected by the size of the canopy and spike, and crop × environment interactions post-anthesis, respectively (Slafer, 2007). In the non-compacted soils, increased yield potential is positively correlated with number of grains per m^2 that result from increased number of grains per spike due to the absence of water stress (Slafer and Andrade, 1993). The other yield components that can be an indicator to the yield of wheat crop is the aboveground biomass (Foulkes et al., 2007), so that higher grain yields are expected in crops that have higher biomass at maturity (Austin, 1982). Total aboveground biomass at pre-harvest, TGW, number of spikes and number of grains within this work showed significant differences between traffic systems, which therefor demonstrate differences in grain yield. These indicators of yield components reflect crop's sensitivity to soil compaction and fertilizer management. Harvest indices of treated (fertilized) plots observed in this experiment were in the range of the other studies (e.g., Sinclair, 1998; Dai et al., 2016). The reduction of nitrogen-use-efficiency (NUE) and agronomic efficiency (AE) in the non-CTF treatments may be attributed to nutrients stress due to limited access of roots to the subsurface soil layers, and thus the uptake of nitrogen was limited as well. Despite there was no significant differences in NUE between the three N fertilizer types, NUE in both traffic systems increased in the order: UAN > urea > ENTEC, which was consistent with differences in grain yield and yield components between the three fertilizer materials. The lowest rainfall was received during the critical stages of plants from July to the end of August (Figure 1), which may have affected grain yield negatively, particularly in compacted soil as a result of increased the soil resistance to the root exploration during this period (Hakansson and Lipiec, 2000).

Modeling of crop performance

As also shown from this study, soil compaction affects crop growth and development through reduced moisture storage (Figure 11), and roots uptake ability (Barraclough and Weir, 1988). The simulated yield reduction for soil compaction from this study was smaller than those found for some similar studies involving wheat, grown under subtropical climate. For example, studies by Radford et al. (2007) and Antille et al. (2016) found a yield reduction from soil compaction of 43% and 53%, respectively. These discrepancies can be attributed to the soil type where wheat crop in this study was grown on Red Chromosol which has a higher drainage porosity (SAT-DUL; Table 2), than Vertosol soils used by the others. A higher drainable porosity allowed greater infiltration even under compaction, leading to greater water loss in the form of drainage which was otherwise used by crop for physiological activities. During drier conditions, moisture is more limiting for crop performance. Therefore, a greater yield and WUE reduction is as expected from soil compaction, as it limits the moisture supply for crop performance. Whereas, a higher runoff during cropping period under wetter conditions but relatively lower reduction in the associated yield under both CTF and non-CTF suggests that increased runoff loss had little effect in reducing biomass or yield. This is because moisture was a less-limiting factor under higher rainfall conditions and any reduction in infiltration or increases to runoff from soil compaction may have insignificant effect on the stored soil water. This effect is especially prominent for Red Ferrosol soil type; as associated higher drainable porosity will still allow enough water to pass through the root zone, filling the root zone with water. Similar conclusion was drawn elsewhere for Red Ferrosol soil (Bell et al. 1997), where improvements to infiltration rate was found little effect on increasing stored soil water due to infiltration amount frequently exceeding the soil's water holding.

While this study captured the seasonal differences in crop physiology and water balance under soil compaction to a great degree, this work is limited by its inability to represent the full extent of the mechanisms by which soil compaction promotes runoff. Although the model can account changes in conductive properties due to soil compaction (e.g. through K_{SAT} values), these effects were poorly impacted the crop productivity on the studied Red Ferrosol soil especially due to associated higher drainable porosity. Thus, the accuracy of the modelled effects of soil compaction on water balance and crop productivity relied mainly on the assumptions on runoff curve number. Field studies are needed to derive improved runoff curve number according to the extent of soil compaction (including surface sealing properties) and associated changes in soil water balance.

Economic considerations

Yield-to-N responses were also tested under linear function and results shown in Table 4. The responses were not significant for both traffic systems and the three fertilizer materials, with the exception of the CTF × ENTEC and non-CTF × urea ($P < 0.05$). The quadratic functions may be justified as all responses produced acceptable fits ($R^2 \geq 79$) with all fertilizer formulations under both traffic systems. This appears to be a fair justification according to the study of Sparrow (1979). Quadratic models provide a more satisfactory biological description of the yield-to-N response, and therefore may be used regardless of non-statistical significance of the quadratic term (Shaohua et al., 1999).

Table 4. Grain yield-to-nitrogen responses relationships tested by using linear functions.

Treatments		Response	P-value	SE	R^2
CTF	UAN	$y = 2907 + 2.5x$	0.23	323	0.59
	ENTEC	$y = 2742 + 2.7x$	0.03	113	0.93
	Urea	$y = 2957 + 0.8x$	0.63	382	0.10
non-CTF	UAN	$y = 2598 + 1.4x$	0.52	424	0.22
	ENTEC	$y = 2504 + 1.9x$	0.81	218	0.66
	Urea	$y = 2483 + 2.1x$	0.03	93	0.92

To simplify the economic analyses, the changes in GM were investigated with regards to the price of the nitrogen (P_C) and the grain (P_C) and the relationship between them which is expressed by means of the price ration (P_R). The price ratio in this research was different between the treatments depending on (P_N) only, because the price of grain (P_C) was constant. The value of the constant price (price of wheat) was taken at the harvest season of 2015, which was equivalent to AUD 0.28 kg^{-1} as recorded in Table 3. The gross margins were investigated for CTF and non-CTF systems, and the tillage systems that might be used with the traffic systems were also investigated. In Australia, zero tillage (ZT) is practiced by most growers who have converted to CTF system (Tullberg, 2007), with some exceptions (Dang et al., 2017), which therefore, only ZT was considered in the assumption that made for CTF system. The gross margin was (≈ AUD 50 ha^{-1}) higher in CTF, which received (7%) greater gross income compared with non-CTF system when shallow tillage is practiced, and 4% when ZT is practiced. Gross margin was more sensitive to the price of crop than the price of N, which agreed with the study investigated by Antille et al., (2017).

Conclusions

The main conclusions derived from this study are:

1. The agronomic performance of wheat was improved in CTF compared with non-CTF by up to 12% for grain yield. The yield improvement by approximately 350 kg ha^{-1} was possible under CTF condition, which subsequently improved gross margin in the first year of converting to CTF by up to AUD 30 ha^{-1}, and AUD 50 ha^{-1} if a zero-tillage, and a shallow tillage were practiced, respectively.
2. Differences in grain yield and yield-to-nitrogen responses between CTF and non-CTF systems were more affected by traffic system than N fertilizer formulations, which confirmed that soil compaction is the main driver for the changes of crop-growth.
3. Under the simulated conditions of this study, it was shown that the impact of soil compaction represented by CTF and non-CTF during drier rainfall conditions on grain yields was higher than those of wetter conditions. Therefore, the greater benefits associated with CTF system are for dryland farming systems. Water-use-efficiency was relatively higher in the drier conditions than in the wetter, which is considered as another benefit for adopting CTF in the dryland cropping system.

Based on the field experiment, and the use of APSIM for simulating long-term effects of CTF adoption on crop and soil, the main benefits of CTF are enhancing agronomic performance by reducing the risk of soil compaction induced by traffic of farm machinery. Results derived from this research confirm the hypotheses formulated prior to this study and therefore are supportive of increased adoption of CTF in Southern East Queensland.

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A.2. **Hussein, M A**, Antille, D., Kodur, S., Chen, G & Tullberg, JN, 'Controlled traffic farming improves nitrogen fertiliser use efficiency in sorghum (*Sorghum bicolor* L.): Field investigations and modelling', submitted to the *Experimental Agriculture.*

Controlled traffic farming improves nitrogen fertiliser use efficiency in sorghum (*Sorghum bicolor* L.): Field investigations and modelling

Abstract

Compaction adversely affects the physical properties of soils and the ability of crops to efficiently use water and nutrients, and therefore reduces the amount of fertiliser recovered in grain. This study investigated the effect of traffic compaction on sorghum response to nitrogen (N) fertilisation. Nitrogen fertiliser was applied at rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1} using urea (46% N), urea-ammonium nitrate (UAN, solution, 32% N) and ENTEC® (3,4-dimethyl pyrazole phosphate treated urea). The APSIM farming system model was used to explore the long-term effects of rainfall variability on crop yield and soil water balance under controlled traffic farming (CTF) system in comparison with non-controlled traffic system. Results show that the measured grain yield was 45% higher in the traffic treatment representative of CTF compared with that of the non-CTF, and this was consistent with differences ($P<0.05$) in all measurements of crop yield components (total aboveground biomass, harvest index, and thousand-grain weight). Fertiliser type had no effect on grain yield, which confirmed that traffic compaction was the main factor affecting crop performance and N recovery in grain and biomass. The optimum N application rates were 145 and 100 kg ha^{-1} N for CTF and non-CTF, respectively; which corresponded to grain yields of 3430 and 1795 kg ha^{-1}, and agronomic efficiencies of 24 and 17 kg kg^{-1}. Simulation study shows that the median yield reduction under non-CTF was similar to those of observed (33 % higher) compared to CTF; with a further 14 % yield reduction in drier years than the median. Modelled water-use-efficiency (WUE) was up to 40% higher in the simulated CTF compared with non-CTF. Given current price ratios (nitrogen-to-grain) and fertiliser type used, gross margin penalties of AUD 75 per ha may be incurred in non-CTF systems compared with CTF when zero-tillage is practiced, and about double when shallow tillage is practiced. This study also showed that N use efficiency cannot be significantly increased if the mechanization system does not allow for avoidance of traffic compaction. Therefore, the benefits of enhanced efficiency fertilisers may not be fully realised if soil compaction is not appropriately managed. Improved soil structural conditions are therefore a pre-requisite for increased fertiliser use efficiency.

Keywords: Controlled traffic, Nitrogen use-efficiency, APSIM, Soil compaction, sorghum.

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Abbreviations: CTF, controlled traffic farming; MERN, most economic rate of nitrogen; NUE, nitrogen use efficiency; TN, total nitrogen; UAN, urea-ammonium nitrate; HI, harvest index; GM, gross margin; A_E, agronomic efficiency; DMPP, dimethyl pyrazole phosphate; TVC, total variable costs.

Introduction

This article, the second in a series of two, reports the results of field and modelling investigations into the short and long-terms effects of controlled traffic farming system on sorghum responsiveness to nitrogen fertilisers and derive the optimum N rate compared with non-controlled system. The first article (Hussein et al., submitted) deals with the agronomic and economic assessments of wheat crop as affected by controlled and non-controlled traffic of farm machinery. These two articles comprise experimental and modelling data, to demonstrate the potential agronomic and economic benefits of adopting CTF in grain cropping. The dataset reported complemented by Tullberg et al., (2018) in to the potential of CTF to reduce soil emission.

Despite soil compaction can occur naturally by wetting and drying (Larson and Allmaras, 1971), compaction induced by machinery traffic is ranked as a major problem facing a cropping sector in several parts of the world (e.g., Van den Akker and Canarache, 2001; Hamza and Anderson, 2005; Houšková and Montanarella, 2008). The main factors that can increase the impact of compaction on soil properties and crop yield are many, such as weather, soil types and moisture content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson et al., 1994; Chamen et al., 2003; Gregorich et al., 2011). For instance, intensive random traffic of farm machinery has large effects on a number of key soil properties such as bulk density, mechanical impedance, porosity and hydraulic conductivity (Hamza and Anderson, 2005), which can potentially reduce root penetration, water extraction and plant growth and thus lead to reduction in crop yield (Kirkegaard et al., 1992; Passioura, 2002).

In Australia, up to 60% of the farm area is likely to be trafficked by heavy machinery annually using minimum tillage system and 80-90% of the cropping area might experience wheel traffic at least once a year with conventional farming practice (Radford et al., 2000; Tullberg, 2010). The controlled traffic farming (CTF) system can reduce compaction induced by machinery and trafficked area to 15-20% of the total land (Tullberg, 2000). The main concept of this cropping system is completely and permanently separating the tramlines and the seed beds (ACTFA, http://actfa.net/). This system can provide favourable conditions and requirements to machinery and plants by improving the tractive efficiency for the machinery and enable root elongation and plant growth in the cropping zone. Adopting of CTF system is a main key to manage soil compaction and consequently reduce soil emissions (Li et al., 2007, 2008; Vermeulen and Mosquera, 2009; McPhee et al., 2015). Avoidance of traffic compaction through adoption of CTF systems has the potential to either reduce nitrogen (N) Fertiliser inputs without compromising crop yield or increase crop yield for the given fertiliser input. This is supported by studies showing enhanced structural conditions in soils established under CTF (e.g., McHugh et al., 2009) and by enhanced nutrient uptake in the absence of traffic compaction (e.g., Lipiec et al., 2003).

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Previous research that looked into soil compaction has addressed some of the issues associated with nutrient and water-use-efficiency (e.g., Bolson and Kaleita, 2007; Bowman, 2009; Botta et al., 2010; Boyer et al., 2011). Despite known advantages of CTF, the efficiency and the effectiveness of different forms and rates of fertiliser application are not understood for summer sown sorghum (*Sorghum bicolor* L.) grown in subtropical Australian conditions. Similarly, information on the effects of traffic compaction on the actual yield-to-fertiliser response curve from which optimum economic rates can be derived, is limited.

Objectives

The objectives of this study were to: (1) determine the effect of compaction induced by traffic of farm machinery on yield-to-nitrogen response relationships, N-fertiliser use efficiency, and optimum economic application rate of different N fertiliser formulations, (2) conduct technical-economic analysis to quantify the effects of traffic-induced soil compaction on crop's gross margins and economic return as a result of changes in the price of nitrogen fertilisers and grain yield, and (3) determine the long-term impact of simulated conditions of CTF and non-CTF on the agronomic performance and water-use-efficiency using the Agriculture Production System Simulator (APSIM) model; for a dryland wheat crop grown on Red Ferrosol soils under subtropical climate condition.

To achieve this objectives, soil conditions (density) representative of controlled and non-controlled traffic systems were obtained by removing compaction through subsoiling to a depth of approximately 300mm and by performing six passes of a medium-sized tractor, respectively. Sorghum was established and the crop subject to the fertiliser treatments has further described in the next section. Grain yield and agronomic efficiency of applied N fertilisers were determined using different methods. Field data including the data of soil properties and crop were used to guide parameterization and application of the Agricultural Production Systems Simulator (APSIM) model (Keating et al., 2003; Holzworth et al., 2014), which was subsequently used to assess the likely impact of soil compaction on crop productivity.

Materials and methods

Sites description

The experiment was conducted at the University of Southern Queensland (27°36'35.27"S, 151°55'50.62"E) located in Toowoomba (Queensland, Australia) during the summer of 2015-2016. Sorghum was planted in the 2nd week of November 2015 and harvested at the beginning of March 2016. Long and short-term rainfall and temperature records for the experimental site are shown in Figure 1. The average monthly minimum temperature in the experimental site during the season was 15 °C in November 2015, and the highest was 28.7 °C in February 2016. The average monthly maximum and minimum rainfall during the same period were 130 mm in December 2015 and 48 mm in March 2016, respectively. December 2015 was recorded highest rainfall by 130 mm compared with other months of the season, which was in the range of long-term (1970-2014) records. Overall, mean air temperatures did not departure significantly from long-term records, despite that minimum temperatures were slightly below average, particularly in early spring.

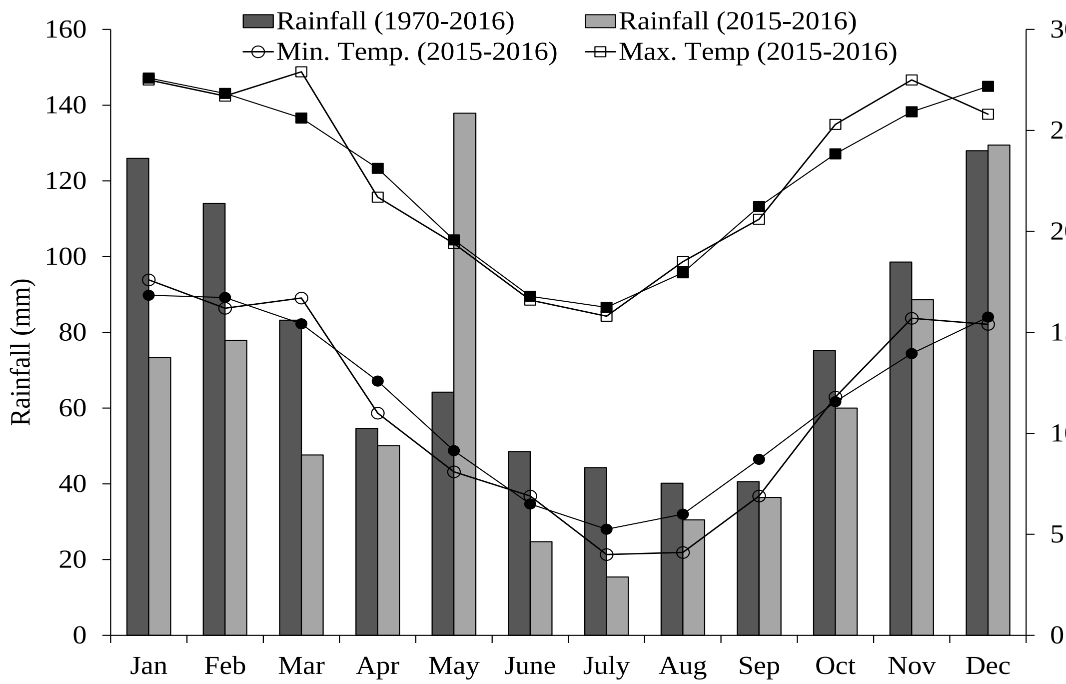

Figure 1. Season (2015-2016) and long-term temperature and rainfall (1970-2016) records in Toowoomba, QLD, Australia (BOM, 2017).

The soil at the site is described in Isbell (2002) as a Red Ferrosol, which is well-drained and has a gentle slope (<0.8%), and it is similar to those frequently occurring in Queensland. Soil textural analyses (Gee and Bauder, 1986) for the bulked 0-200 mm layer were: 69% clay, 11% silt, and 20% sand. There was a requirement to remove historical near-surface compaction at the experimental site to enable the two traffic treatments (CTF and non-CTF, respectively) to be imposed (Godwin, 2011). For this, the soil was first chisel-plowed to a depth of 300 mm. This cultivation depth was chosen based on an earlier study in SE Queensland (Antille et al., 2016), which showed that removal of compaction to such depth was sufficient to return mine-rehabilitated land affected by compaction to satisfactory crop production and that rainfall-use efficiency achieved after cultivation was ≥85% in most years. Soil conditions (density and strength) representative of controlled and non-controlled traffic systems were achieved by removing compaction through subsoiling to a depth of approximately 300mm and by performing six passes of a medium-sized tractor (Belarus 920, 100 HP, gross mass: 3.9 Mg), respectively as demonstrated in the earlier work (Hussein, et al., 2017). Sorghum (*Sorghum bicolor* L.) was sown on 11th of November 2015 at a field-equivalent seeding rate of 2.5 kg ha^{-1}, and subject to standard agronomic practice; except for the fertiliser application, which was dependent on treatment. Sowing was conducted with a 4-row conventional feeder fitted with knife points at 750 mm row spacing.

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The experiment was conducted in two adjacent blocks; namely: CTF and non-CTF, in which 60 plots (dimensions: 4-m × 4-m) with 4 plant rows per plot were laid-out in a completely randomised design, and subject to the fertiliser treatments described here. Three types of fertiliser were used: urea (46% N), urea treated with 3,4-dimethyl pyrazole phosphate (DMPP), commercially known as ENTEC® urea (46% N), and urea ammonium nitrate referred to as UAN (32% N, solution). All fertiliser treatments, including controls, were setup in triplicate (n=3). The fertilisers were hand-applied in a single band (≈50 mm) next to the plant row and incorporated at N rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1}. For all fertiliser treatments, the application of N fertiliser was split into two dressings for the rates of 200 and 300 kg ha^{-1} N: applied on 30- November and the second dressing was applied about two weeks later on 11th of December.

Soil physical properties

Soil bulk density (ρ_b) was determined for the 0-300 mm depth layer at regular increments of 100 mm by taking soil cores of 50 mm in diameter. Measurements were taken three times (n=3) before and after the traffic treatments were imposed, and ρ_b was determined based on Blake and Hartge (1986) (Table 1). Maximum bulk density derived from the Proctor (BSI, 1975) test was 1.70 g cm^{-3} at a derived soil moisture content of 21.2% (w w^{-1}). Total porosity of soil was derived from density properties based (McKenzie et al., 2002) using a nominal particle density of 2.65 g cm^{-3}, which was considered to be appropriate for the range of soil types investigated (Hurlbut and Klein, 1977). Soil penetration resistance was measured by pushing a cone (125 mm^2 base area, 30° apex angle) into the soil to a depth of 500 mm at constant speed (0.05 m s^{-1}), and by digitally recording the force at 25 mm depth increments based on ASABE Standard EP542 (ASABE, 2013). Gravimetric soil moisture content was simultaneously determined because of its influence on soil strength (Ayers and Perumpral, 1982). Measurements of soil moisture content and soil penetration resistance were conducted ten times (n=10). Soil water infiltration was measured using the double-ring infiltrometer method (Parr and Bertrand, 1960). Infiltration rates were subsequently obtained by differentiating Kostiakov's equation (Eq. 1) with respect to time to describe the relationship between the rate of infiltration and times (Eq. 2). Measurements were replicated three times (n=3).

$$F_t = a \times t^n \tag{1}$$

$$I_t = a \times n \times t^{n-1} \tag{2}$$

Where: F_t is cumulative infiltration (mm) at time t (h), a and n are constants, and I_t is instantaneous infiltration rate (mm h^{-1}) at time t (h).

Saturated hydraulic conductivity (K_{SAT}) of soil was measured for both CTF and non-CTF plots using the constant head test (Klute, 1965). The outflow leachate was collected in beakers at the bottom of the column. The measurements of the leachate and timing of the duration required to obtain leachate enabled K_{SAT} to be determined. The K_{SAT} for a vertical soil core under constant head is found using Eq. 3 (Hillel 2004).

$$K_{SAT} = \frac{VL}{AHt} \tag{3}$$

Where: V is the volume of solution (mm^3), L is the length of the soil core (mm), A is the area of the soil core (mm^2), H is the water head from base of core to top of solution (mm), and t is the time for V to flow through (h).

Drained upper limit (DUL) is the highest field-measured water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible, and DUL is referred to as field capacity. This parameter was measured based on the approach used by Ratliff et al., (1983). Soil $pH_{1:5}$ and electrical conductivity ($EC_{1:5}$) were 6.22 and 0.07 ds m^{-1}, respectively (Rayment and Lyons, 2011).

Crop measurements and analyses

The crop was harvested by hand-cutting the entire plants from entire plot at approximately 20 mm above the soil surface on 4th of March 2016. These samples were used to determine grain yield, and the following yield components: harvest index (HI), the ratio grain weight-total aboveground biomass (Donald and Humblin, 1976); thousand grain weight (TGW) (MAFF, 1986, Method No.: 73). Total N in grain (MAFF, 1986, Method No.: 48) was used to estimate apparent N recovery in grain by the difference method, and to estimate nitrogen use efficiency (NUE). Differences in yield between fertilized and non-fertilized crops, relative to N applied as fertilizer, were used to denote agronomic efficiency (AE), which was determined for all four crops. These relationships are shown in Eq. [4] and [5], respectively (after Baligar et al., 2001):

$$NUE\ (\%) = \frac{(U_F - U_{F=0})}{N_{Rate}} \tag{4}$$

$$AE\ (\text{kg}\ kg^{-1}) = \frac{(Y_F - Y_{F=0})}{N_{Rate}} \tag{5}$$

Where: NUE is nitrogen use efficiency (%) based on apparent N recovery in grain U_F and $U_{F=0}$ are N recoveries in grain (kg ha^{-1} N) from fertilised- and non-fertilised (control) crops, respectively, and N_{RATE} is N application rate (kg ha^{-1}). AE is agronomic efficiency (kg kg^{-1}), Y_F and $Y_{F=0}$ are grain yields (kg ha^{-1}) corresponding to fertilised- and non-fertilised (control) crops, respectively.

Yield-to-nitrogen response relationships were examined by applying nonlinear regression analyses, and by fitting quadratic functions to the data (Abraham and Rao, 1965). The approach used in this work is from studies (e.g., Kachanoski, 2009; Antille et al., 2017) dealing with cereal crop responses to applied N fertiliser, and assumes a quadratic-plateau relationship. Crop's gross margin (GM) was estimated as the difference between gross income (GI) and total variable costs (TVC). This analysis uses the N_{RATE} as the optimum N application rate (MERN), which is derived from the yield-to-nitrogen response relationship. This is used to estimate the fertiliser component of the variable costs and also to derive the corresponding grain yield from the yield-to-nitrogen response curve. Therefore, GM reflects the gross profitability of the crop when the fertiliser N input is optimised.

The components of the total costs were categorized to variable and constant costs. Seed, operations, and agro-chemical costs were identical costs in both traffic systems. Seed cost included costs of seed and seed treatments, and the operations cost included the costs of fuel, repairs and maintenance of agricultural machinery. A simplification was made by assuming that variable costs were identical in both traffic systems; except for the fertilizer costs, which were dependent on fertilizer treatment. In well-design CTF systems in Australia, the area subject to traffic typically occupies 15% (or less) of the cultivated field area, particularly when permanent no-tillage is practiced. By contrast, where CTF is not practiced, this area is often greater than 65% when shallow tillage is practiced and 45% when no-tillage is practiced, and it can be as high as 85% in conventional tillage systems that require primary tillage operations prior to crop establishment (Kroulík et al., 2009). In Australia both tillage systems are using, which therefore GM calculations were adjusted to reflect the effect on yield of the relative areas affected by traffic compaction in typical CTF and non-CTF systems, respectively. For shallow tillage, it was assumed that 65% and 35% of the cultivated area in the non-CTF system was and was not subject to traffic compaction, respectively. While when zero-tillage (ZT) is practiced, it was assumed that 45% and 55% of the cultivated area in the non-CTF system was and was not subject to traffic compaction, respectively. For the CTF system, these relative areas were 15% and 85%, respectively. Hence, the corresponding GI for each traffic system was derived by adjusting Y_{MERN} in Equations (Eq. 6), (Eq. 7) and (Eq. 8) by these relative percentages, respectively. This was considered to be a fair assumption based on earlier studies (e.g., Galambošová et al., 2017).

$$Y_{MERN}(non-CTF) = [(Y_{MERN}(CTF) \times 0.35) + (Y_{MERN}(non-CTF) \times 0.65)] \quad (Shallow\ tillage) \qquad (6)$$

$$Y_{MERN}(non-CTF) = [(Y_{MERN}(CTF) \times 0.55) + (Y_{MERN}(non-CTF) \times 0.45)] \quad (Zero-tillage) \qquad (7)$$

$$Y_{MERN}(CTF) = [(Y_{MERN}(CTF) \times 0.85) + (Y_{MERN}(non-CTF) \times 0.15)] \qquad (8)$$

Where: Y_{MERN} is crop yield correspondent to MERN (kg ha^{-1}); CTF and non-CTF are controlled and non-controlled traffic farming systems, 0.65 and 0.35 are the relative areas that was and was not subject to traffic compaction, respectively, under non-CTF system when 'shallow tillage' is practiced; 0.45 and 0.55 are the relative areas that was and was not subject to traffic compaction, respectively, under non-CTF system when 'zero tillage' is practiced; 0.15 and 0.85 are the relative areas that was and was not subject to traffic compaction, respectively, under CTF system. This assumption is considered to be an appropriate as ZT is practiced by most growers who have converted to CTF system (Tullberg, 2007), with some exceptions (Dang et al., 2017).

Modelling of crop performance

Modelling of crop performance was conducted using the Agriculture Production System Simulator (APSIM) farming systems framework (Holzworth et al., 2014). Full documentation for APSIM's modules, mathematical structure and source codes can be found at www.apsim.info/documentation/. A process modelling approach was chosen to quantify the long-term impact of soil compaction on crop phenology, as described previously (Antille et al., 2016). Simulations involved testing of water use efficiency, biomass, and yield under CTF and non-CTF system on summer sown (November-January) sorghum. The simulation conducted for 56 years (1961 to 2016) and the results were grouped as rainfall classes (driest 30%, wettest 30% and average 40% years) to understand the rainfall variability on crop performance. The soil was a Red Ferrosol (Isbel, 2002) and the climate data was obtained from Australian Bureau of Meteorology weather station (41529) at Toowoomba (QLD), via patched point data set (Jeffrey et al., 2001).

Measured soil data was used to represent drained upper limit (DUL) and saturated water content (SAT), and bulk density (BD) for CTF and non-CTF conditions to a depth of 300 mm, except for saturated hydraulic conductivity (K_{SAT}) which was measured to a depth of 150 mm. The bulk density data for 300 to 1800 mm depth and K_{SAT} for 150 to 1800 mm depth for CTF condition were derived and modified from measured data on similar Red Ferrosol soil (Dalgliesh and Foale, 1998; Connolly et al., 2001). Pedotransfer functions were fitted for CTF condition, to estimate lower limit (LL) water content for all soil depths (0 to 1800 mm), and DUL and SAT water contents for the deeper depths (300 to 1800 mm), using particle size analysis data derived via the Pipet method (Gee and Bauder, 1986). For non-CTF conditions, these data were obtained from field data and a series of assumptions as described earlier (Antille et al., 2016). A runoff curve number (i.e. runoff as a function of total daily rainfall), which describes runoff potential for bare-soil, was set at 73 units for CTF (Kodur et al., 2014); and was increased by 7 units for non-CTF conditions based on an earlier study by Owens et al., (2015). Default soil evaporation parameters were set according to Kodur (2017). These parameters are the one that comes as a default with the APSOIL database. Various soil properties and input parameters used in the model are presented in Table 1.

Sorghum was sown every year on defined sowing rainfall (at least 25 mm over a 7-day period between Nov-Jan. If the defined rainfall did not occur, the model was forced to sow a crop on 31st January so that cropping can occur every year. Sorghum was sown at 14 plants m^{-2}, and received a N application rate of 140 kg N ha^{-1}, which corresponded with the optimum N application rate in the form of urea (Table 2). Nitrogen was applied 30 days after sowing, which was consistent with standard agronomic practice (Gerik et al., 2003). Initial moisture at the first year of study was 95% of maximum available water capacity and was obtained by prior running the model for 10 years. APSIM has been broadly tested across soil and climate conditions in Australia and internationally for a range of experimental conditions (e.g., Hammer et al, 2010; Whish et al., 2005). However, to further represent the conditions of the current field study, the model was calibrated for both CTF and non-CTF conditions, and validated against the yield data obtained from field (Table 1). The modelled yield was 10% higher than those measured and consider this difference was reasonable to achieve the study objective. Water-use-efficiency is defined in this study as the ratio of grain yield (kg ha^{-1}) to total rainfall that received during the corresponding season (Hochman et al., 2009).

Table 1: Soil properties used in the simulations† for CTF and non-CTF farming conditions for a Red Ferrosol soil at Toowoomba, Qld, Australia. The standard deviation (SD) is shown for measured values as ± the mean value (n = 3), except when not shown (*n* = 1). Note: BD, bulk density; LL, lower limit, DUL, drained upper limit; SAT, saturation water content, and KS, saturated hydraulic conductivity.

Depth (mm)	BD ($g\ cm^{-3}$)	Total porosity (%)	Plant LL ($m^3\ m^{-3}$)	DUL ($m^3\ m^{-3}$)	SAT ($m^3\ m^{-3}$)	K_S ($mm\ day^{-1}$)
CTF						
0-150	1.22±0.06	54±0.02	0.210	0.300±0.02	0.550	1000±6.65
150-300	1.20±0.03	55±0.02	0.240	0.340±0.01	0.550	500
300-600	1.20	55	0.220	0.360	0.480	100
600-900	1.20	55	0.240	0.350	0.440	50
900-1200	1.22	54	0.250	0.360	0.430	50
1200-1500	1.25	53	0.250	0.330	0.400	25
1500-1800	1.30	51	0.270	0.330	0.400	25
non-CTF						
0-150	1.37±0.05	49±0.01	0.220	0.265±<0.01	0.482	50±0.08
150-300	1.38±0.04	48±0.01	0.250	0.290±<0.01	0.495	25
300-600	1.30	51	0.236	0.365	0.442	10
600-900	1.28	52	0.253	0.354	0.410	25
900-1200	1.28	52	0.261	0.364	0.407	25
1200-1500	1.27	52	0.254	0.331	0.392	25
1500-1800	1.32	50	0.274	0.331	0.392	25

† Data for BD, DUL, SAT and K_S data for 0 to 300 mm depth were directly measured in the field, data for 300-1800 mm depth were derived using pseudo-transfer function (DUL and LL from particle size analysis; K_{SAT} was based on adjustments using Red Ferrosol soil data by Connolly et al. (2001) and APSOIL database (Dalgliesh and Foale, 1998). Data for non-CTF conditions were adjusted based on field conditions, as explained (Antille et al., 2016).

Statistical analyses

Statistical analyses for crop and soil data used Statistical Package for the Social Sciences (SPSS-version 23) software (Swan and Sandilands 1995). Means of cone index were compared for significance using LSD at 5% level of probability, and using Duncan for the rest of means data at the same level of probability. Statistical analyses were graphically assessed by means of residual plots and normalization of data was not required. Yield-to-nitrogen responses were investigated by means of nonlinear (quadratic) regression analyses. Linear regression analyses were also applied to examine the relationships between grain yield and N application rates. Nonlinear regression analyses were used to describe the relationships between nitrogen-use-efficiency and N application rates, from which nitrogen-use-efficiency and agronomic efficiency corresponding to most economic rate of nitrogen were derived. Analytical values are reported as the mean ± standard deviation (SD).

Results

Soil physical properties

Soil penetration resistance (PR) for traffic treatments representing CTF and non-CTF systems is shown in Figure 2. Overall, there were significant differences ($P<0.05$) in PR between CTF and non-CTF, particularly in the 50 to 200 mm depth interval, where penetration resistance was up to 60% higher in non-CTF. Mean values of cone index in the 0-500 mm depth range were 2.5 and 5.1 MPa (LSD 5% level: 1.32) for the CTF and non-CTF systems, respectively. Soil penetrometer resistance in the wheeled plots increased with increasing soil depth, similar to the pattern of bulk density (Table 1). Differences in soil moisture content (w w^{-1}) between the two traffic systems were small (P>0.05).

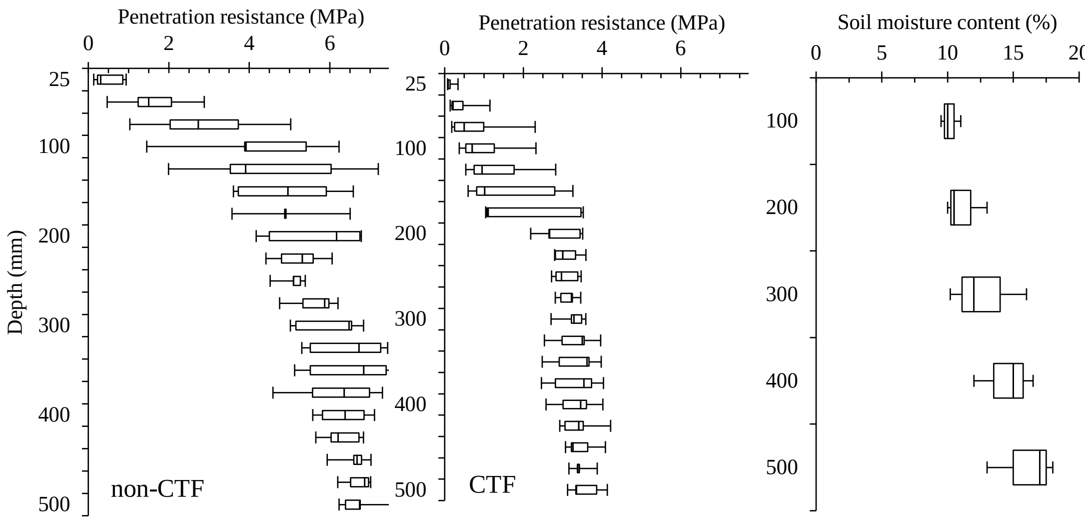

Figure 2. Soil penetrometer resistance profile in CTF and Non-CTF traffic systems, and moisture content. Box plots show Min, Q_1, Med, Q_3, and Max, respectively. Use n = 10 for cone index and moisture content.

Soil water infiltration rates for the CTF and non-CTF are shown in Figure 3. Infiltration rates were significantly lower in non-CTF compared with CTF at any given time (P-values <0.05). Infiltration rates in CTF were approximately double those of the non-CTF system at any given time (mean values of 3.0 and 1.50 mm $min.^{-1}$ for CTF and non-CTF), respectively. These results are consistent with measurements of saturated hydraulic conductivity (K_{SAT}) reported in Table 1, which were 20 times higher (P < 0.05) in CTF compared with non-CTF (e.g., 1000 mm day^{-1} vs. 50 mm day^{-1}, respectively).

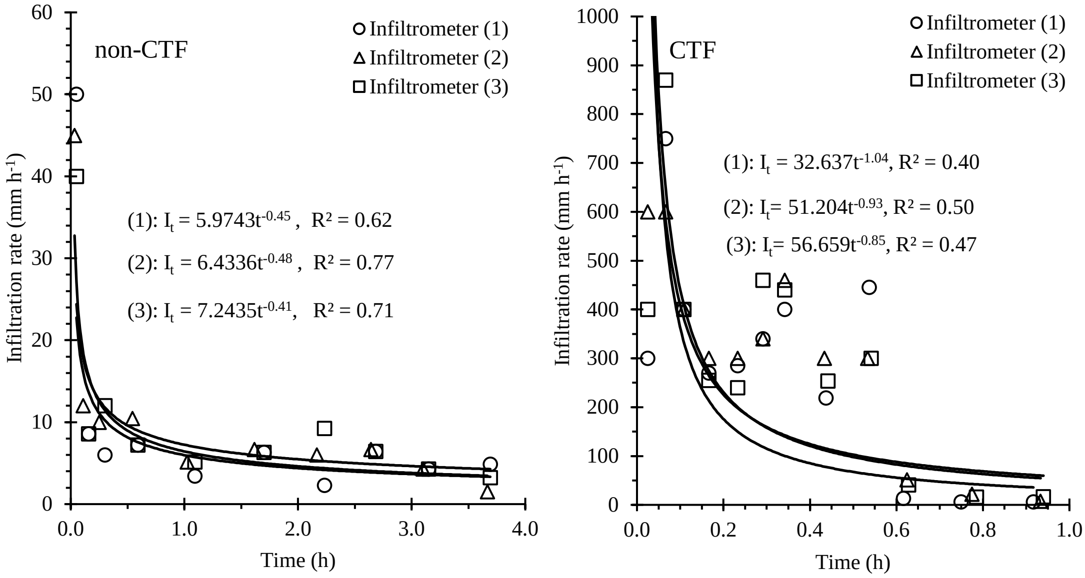

Figure 3. Relationship between infiltration rate (I_t, mm h^{-1}) and time (*t*, h) recorded at the experimental site for the two traffic treatments. Use P<0.05. Data from Hussein et al., (2017).

Grain yield and yield components

There were significant differences in grain yield and yield components between the two traffic systems as well as between fertilized (treated) and non-fertilized crop (controls), which were observed in both traffic systems ($P<0.05$). Yield components were also significantly affected by traffic system and nitrogen application rate ($P < 0.05$).

Comparisons between controls showed that grain yield was about 480 kg ha^{-1} greater in CTF compared with non-CTF ($P < 0.05$). The fertilized crop under CTF system was approximately 1400 kg ha^{-1} higher compared with non-CTF ($P < 0.05$). The optimum N application rates (MERN), and corresponding grain yield, were 145 kg ha^{-1} N and 3428 kg ha^{-1}, and 100 kg ha^{-1} N and 1796 kg ha^{-1} for CTF and non-CTF, respectively. The effect of fertiliser type on the grain yield and yield components was not significant ($P > 0.05$), which suggested that compaction was the main factor influencing the response to applied N fertilizer (Figure 4). Thus, grain yield was relatively more sensitive to soil compaction than fertilizer N formulation. This effect was consistent at any given rate of nitrogen fertilizer.

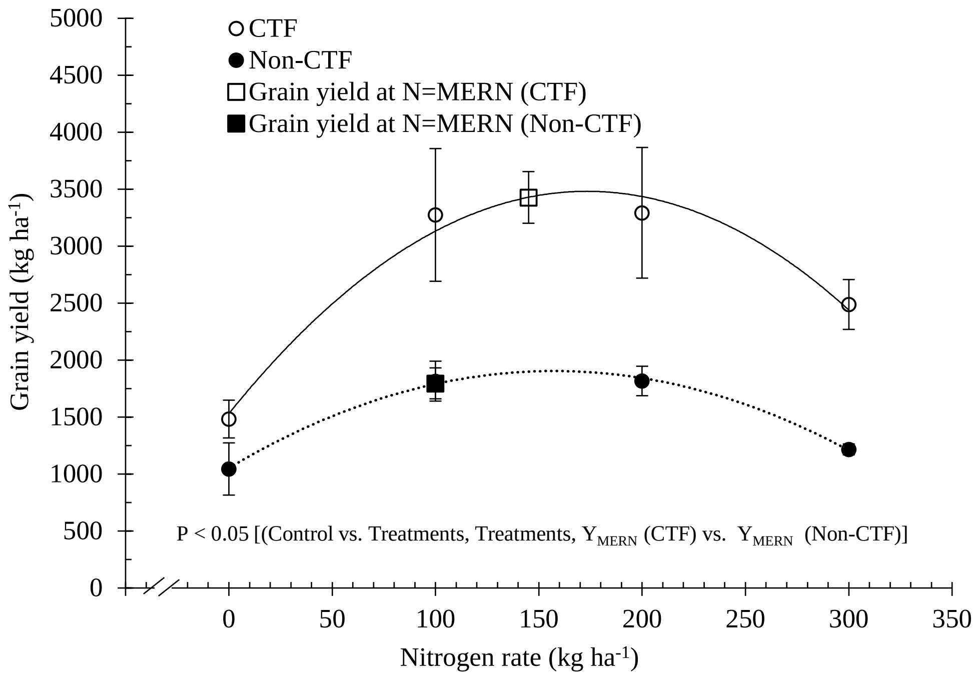

Figure 4. The relationship between nitrogen application rates and grain yield under CTF and non-CTF systems. Error bars denote standard deviation (SD) of mean (n = 9, except for N = 0 and N=MERN, n=3). Control (N = 0), treatments (N ≠ 0)

There were significant differences in aboveground biomass between treated-traffic crop and controls, which were observed in both traffic treatments (P<0.01). The highest value of biomass was observed in fertilized CTF plot (8140 kg ha^{-1}) compared with fertilized-treated crop in non-CTF which was recorded 5989 kg ha^{-1} (Figure 5 a). The N application rate had also a significant impact on biomass (P<0.05). Overall, the average aboveground biomass was 28% greater in CTF compared with non-CTF system.

Differences in harvest index between treatments and controls were significant in both traffic systems as well as between CTF and non-CTF (P<0.05). Harvest indices were higher when fertiliser was applied at rate of 200 kg ha^{-1} N, which was in accord with estimates of optimum N application rates (Figure 5 b).

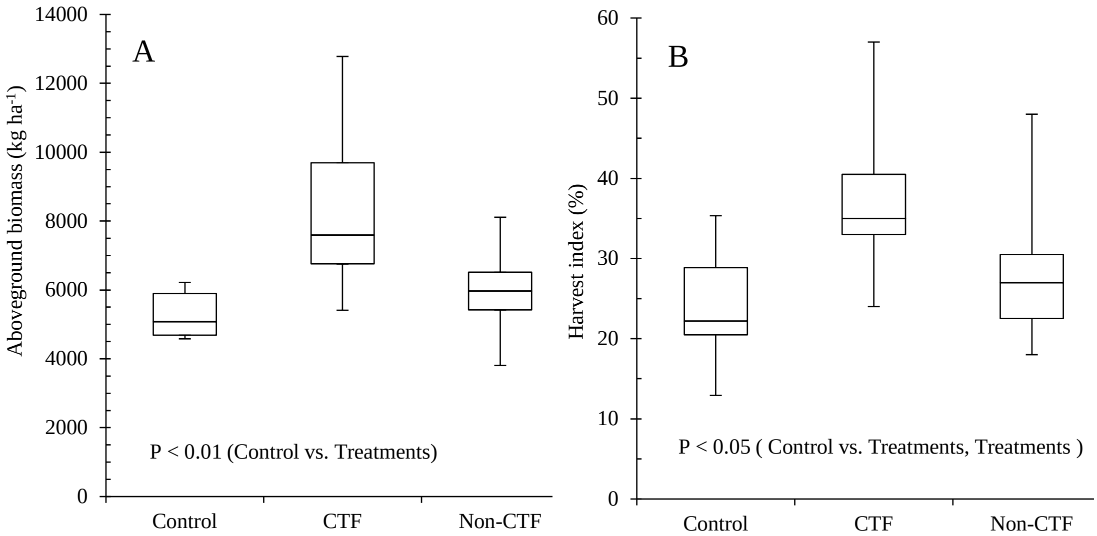

Figure 5. (A) aboveground biomass, and (B) harvest index as affected by controlled and non-controlled traffic of farm machinery. Box plots show Min, Q_1, Med, Q_3, and Max, respectively. Use n = 6 for control (N = 0), and n = 27 for traffic treatments (N ≠ 0).

Nitrogen uptake and nitrogen fertiliser use efficiency

Total N in grain (TN) was significantly higher in fertiliser-treated compared to control in both traffic systems, particularly in CTF system (P<0.05), but the difference between the two traffic treatments was not significant (P > 0.05), which was about 5% greater in CTF compared with non-CTF (Figure 6 a). Nitrogen content were about 10% lower in controls compared to fertiliser treatments. These differences were consistent with nitrogen uptake, which observed in CTF up to 45% compared with non-CTF, and 60% compared to controls (Figure 6 b). Despite this, the difference in N recoveries between non-CTF and controls was not significant (P>0.05).

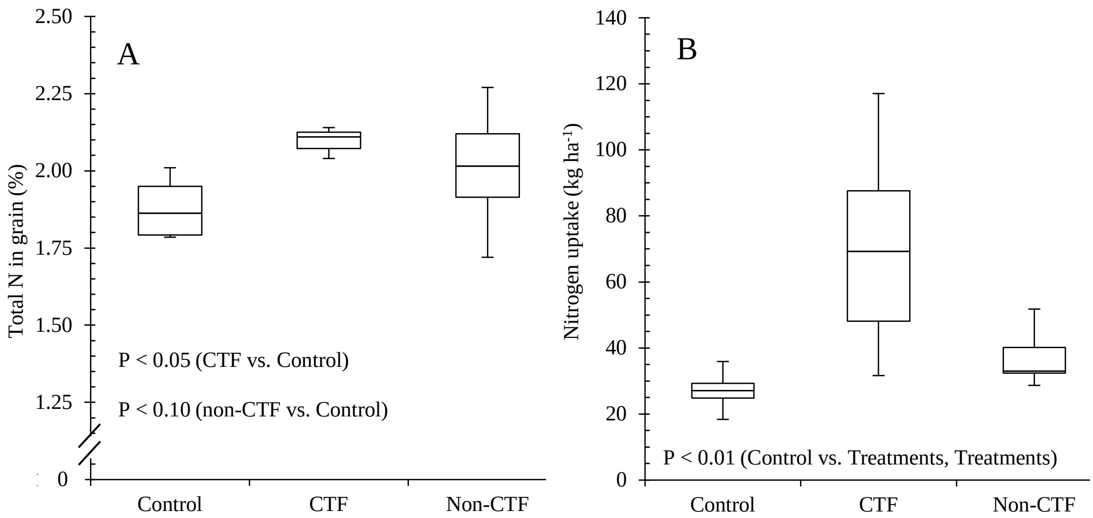

Figure 6. Traffic treatment effects on total grain-N (A) and N recovery in grain (B), respectively. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively. Use n = 6 for control (N = 0), and n = 27 for traffic treatments (N ≠ 0).

The traffic treatments had significant effects on nitrogen use efficiency (NUE) (P<0.05), and this value was higher by up to 60% in CTF compared with non-CTF as shown in Figure 7. The effect of fertiliser type was not significant (P>0.05) and confirmed a significantly greater effect of compaction on NUE. The value of NUE that corresponds with the optimum N application rate was derived from the nitrogen use efficiency-to-N rate response relationships shown in Figure 7. This shows that if N was to be applied at the optimum rate (MERN), NUE is expected to be approximately 45% higher in CTF compared with non-CTF.

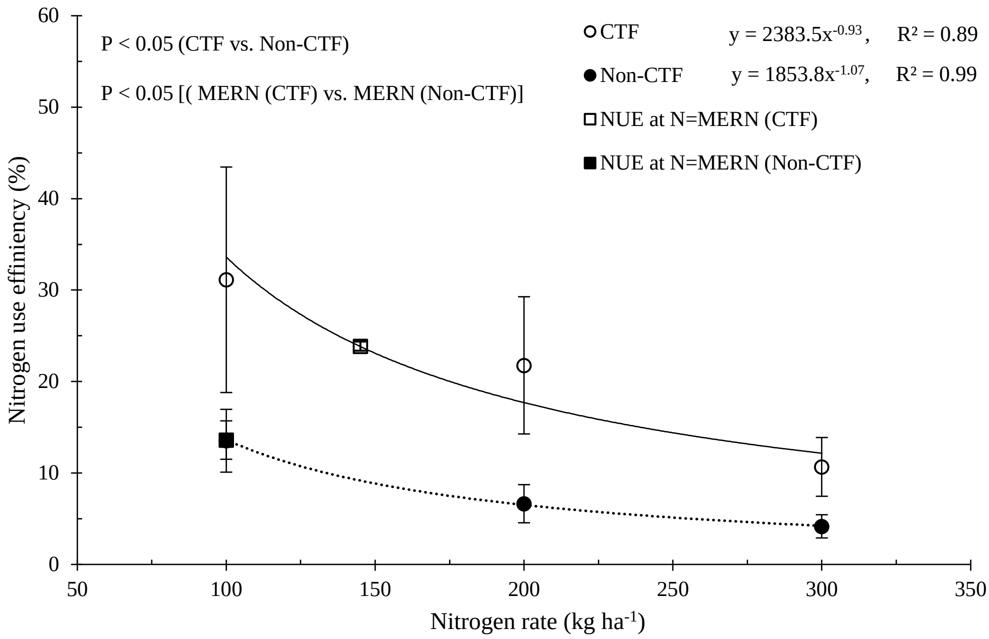

Figure 7. The relationships between nitrogen application rates and nitrogen use efficiency under CTF and non-CTF systems. Error bars denote standard deviation (SD) values at n = 9 (except n = 3 for N=300 and N=MERN).

Agronomic efficiency (AE) was approximately 40% greater in CTF compared with non-CTF (10 *vs.* 4 kg kg^{-1} for CTF and non-CTF systems, respectively), as shown in Figure 8. However, the agronomic efficiency at the optimum N rate (MERN) was insignificantly higher by 16% in CTF compared with non-CTF (P>0.05) (≈ 11.5 vs. 9.6 kg kg^{-1}, respectively). Similarly, there was not fertiliser type effect on AE, which was therefore consistent with NUE calculations and also suggested a stronger compaction than fertiliser formulation effect on grain yield.

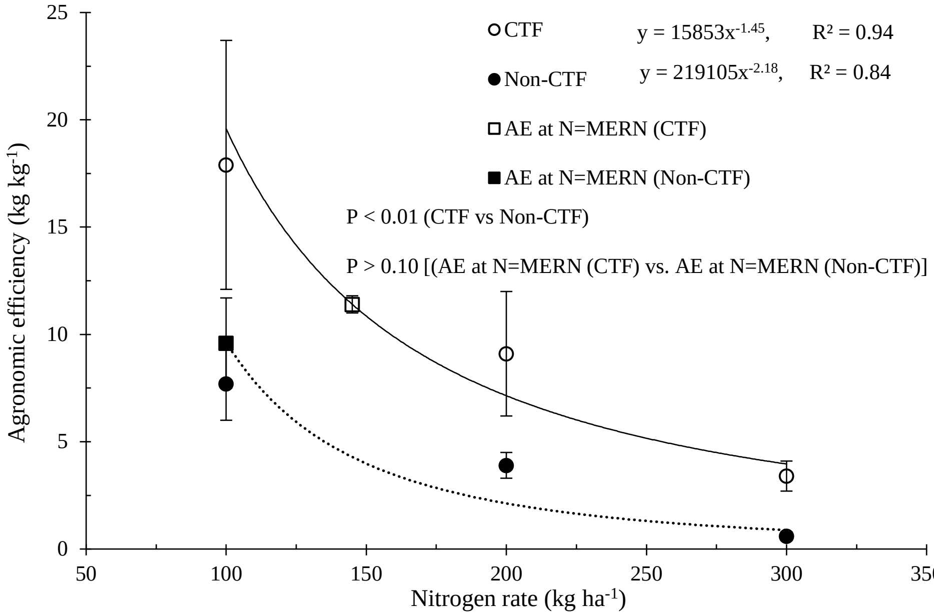

Figure 8. The relationships between nitrogen application rates and agronomic efficiency under CTF and Non-CTF systems. Error bars denote standard deviation (SD) values at n = 9 (except n = 3 for N=MERN).

Economic analysis

Table 2 shows the most economic rate of N (MERN) and corresponding yield (Y_{MERN}) derived from the yield-to-nitrogen response relationships, and price ratios (P_R) for the year of harvest. With the exception of urea under CTF, yield-to-nitrogen responses were not significant when quadratic models were fitted to the data, which were observed in both traffic systems ($P > 0.05$). Despite this, responses were significant at a 10% probability level in non-CTF × UAN. Yield-to-N responses relationships were also tested using linear function, and the responses were not significant for both traffic systems and the three fertilizer materials ($P > 0.05$) as shown in Table 3. At the optimum N arte, the corresponding yields (Y_{MERN}), CTF was 24% higher compared with non-CTF (mean values of 23.72 and 18.17 kg kg^{-1}, respectively).

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Table 2. Economic rate of nitrogen (N_{MERN}) in sorghum and the theoretical application rate for maximum yield response (N_{MAX}) for CTF and non-CTF systems, where price of grain (P_{Grain}); price of nitrogen (P_N); price ratio (P_R); standard error (SE); maximum nitrogen (N_{MAX}); maximum yield (Y_{MAX}); most economic rate of nitrogen (MERN); crop yield at MERN (Y_{MERN}). The standard deviation (SD) is shown as ± the mean value, use n = 12.

Treatments		P_{Grain}	P_N	P_R	Response	P-value	SE	R^2-value	N_{MERN}	Y_{MERN} (SD)	N_{MAX}	Y_{MAX}
		(AUD kg^{-1})		- -	- - -	- - -	- - -	- - -	($kg\ ha^{-1}$)			
non-CTF	UAN	0.23	0.77	3.3	$y = 1029 + 13.5x - 0.04x^2$	0.07	69	0.99	117	2012 (504)	156	2077
	ENTEC	0.23	0.96	4.2	$y = 1062 + 7.6x - 0.02x^2$	0.16	80	0.97	73	1491 (283)	163	1678
	Urea	0.23	0.75	3.3	$y = 1067 + 11.4x - 0.04x^2$	0.13	102	0.98	111	1884 (429)	156	1957
CTF	UAN	0.23	0.77	3.3	$y = 1527 + 27.9x - 0.08x^2$	0.11	200	0.98	152	3902 (1053)	173	3937
	ENTEC	0.23	0.96	4.2	$y = 1575 + 16.1x - 0.04x^2$	0.34	412	0.88	140	2998 (696)	190	3101
	Urea	0.23	0.75	3.3	$y = 1488 + 23.5x - 0.07x^2$	0.01	24	0.99	142	3385 (868)	165	3423

UAN = Urea ammonium nitrate (solution, 32%N),

ENTEC = urea treated with 3,4-dimethyl pyrazole phosphate (DMPP, 46% N),

Urea (46% N).

Table 3. Grain yield-to-nitrogen responses relationships tested by using linear functions.

Treatments		Response	P-value	SE	R^2
non-CTF	UAN	$y = 1461 + 0.5x$	0.84	612	0.02
	ENTEC	$y = 1294 + 0.6x$	0.73	333	0.07
	Urea	$y = 1432 + 0.5x$	0.81	520	0.02
CTF	UAN	$y = 2336 + 3.7x$	0.55	1151	0.20
	ENTEC	$y = 1999 + 3.4x$	0.37	667	0.39
	Urea	$y = 2203 + 2.1x$	0.74	1012	0.10

The gross margin (GM) in CTF system increased significantly by approximately 34 % compared with non-CTF (P > 0.05), when shallow tillage is practiced, and up to 25% when zero-tillage is practiced. Despite this, the difference was significant at a 10% probability level (Table 4) when shallow tillage is practiced with CTF system. Differences in GM between fertiliser types are mainly due to differences in the cost of N, particularly for ENTEC, which indicated approximately 1000 AUD per t. The impact of fertiliser-N cost on gross margin was therefore higher for the non-CTF system due to overall lower yield.

Table 4. Gross income (GI), total variable cost (TVC), and gross margin (GM) obtained from sorghum based on the MERN and Y_{MERN} presented in Table 2. Constant cost is AUD 169.11 ha^{-1}. Use AUD1 ≈ USD 0.75.

Treatments		**GI (AUD ha^{-1})**		**Fertilizer Cost**	**TVC**	**GM (AUD ha^{-1})**	
		ZT[1] (45%)	ST[2] (65%)	AUD ha^{-1}	AUD ha^{-1}	ZT (45%)	ST (65%)
non-CTF	UAN	702	615	99	268	434	347
	ENTEC	534	464	79	248	286	216
	Urea	623	554	92	261	362	293
CTF	UAN	832		126	295	537	
	ENTEC	638		143	312	326	
	Urea	727		115	284	443	

[1] ZT when zero-tillage is practiced; and [2] when shallow tillage is practiced.

Modelling of crop performance

Modelled grain yield, water-use-efficiency (WUE), and biomass under different amount of rainfall for

CTF and non-CTF conditions are shown in Table 5. Soil compaction in non-CTF system caused considerable reductions in these parameters, respectively by 32 %, 38%, and 33% at the median rainfall. Whereas these reductions were prominent across the rainfall conditions, which caused a 12% greater reduction in grain yield for below average rainfall conditions (<30th percentile; mean rainfall = 386 mm/season) than the median rainfall conditions (>70th percentile; mean rainfall = 590 mm/season). The mean difference in WUE between CTF and non-CTF was approximately 40%, and this difference was reduced to in the years that received above average rainfall, which was indicated about 22% (Table 5).

Table 5. Water-use-efficiency, biomass and yield for 56 years of simulated sorghum-fallow cropping system on a Red Ferrosol for CTF and non-CTF. Below average (<30th percentile = 386 mm/season); average (391 mm/season); above average (>70th percentile=590 mm/season).

Rainfall category	Yield (kg ha^{-1})			WUE (kg mm^{-1})			Biomass (kg ha^{-1})		
	CTF	non-CTF	Differences	CTF	non-CTF	Differences	CTF	non-CTF	Differences
Above average	2944	2259	685	5.51	4.11	1.40	8325	6400	1925
Average	3111	2093	1018	7.00	4.61	2.39	8347	5700	2647
Below average	3137	1676	1461	10.68	5.22	5.46	8379	4677	3702
Mean	3064	2009	1055	7.73	4.65	3.08	8350	5592	2758

The negative effects associated with soil compaction on sowing soil moisture and runoff are shown in Figure 9. Soil compaction from non-CTF caused 1.5% reduction in sowing soil moisture, but 46 % increase in runoff compared with that from the CTF soil. The negative effects of soil compaction on sowing moisture and runoff were pronounced with increased in rainfall intensity. That is, for above average rainfall conditions, soil compaction caused a 2% reduction in sowing moisture (Figure 9 a) and a 45 % increase in the runoff (Figure 9 b) than that under CTF.

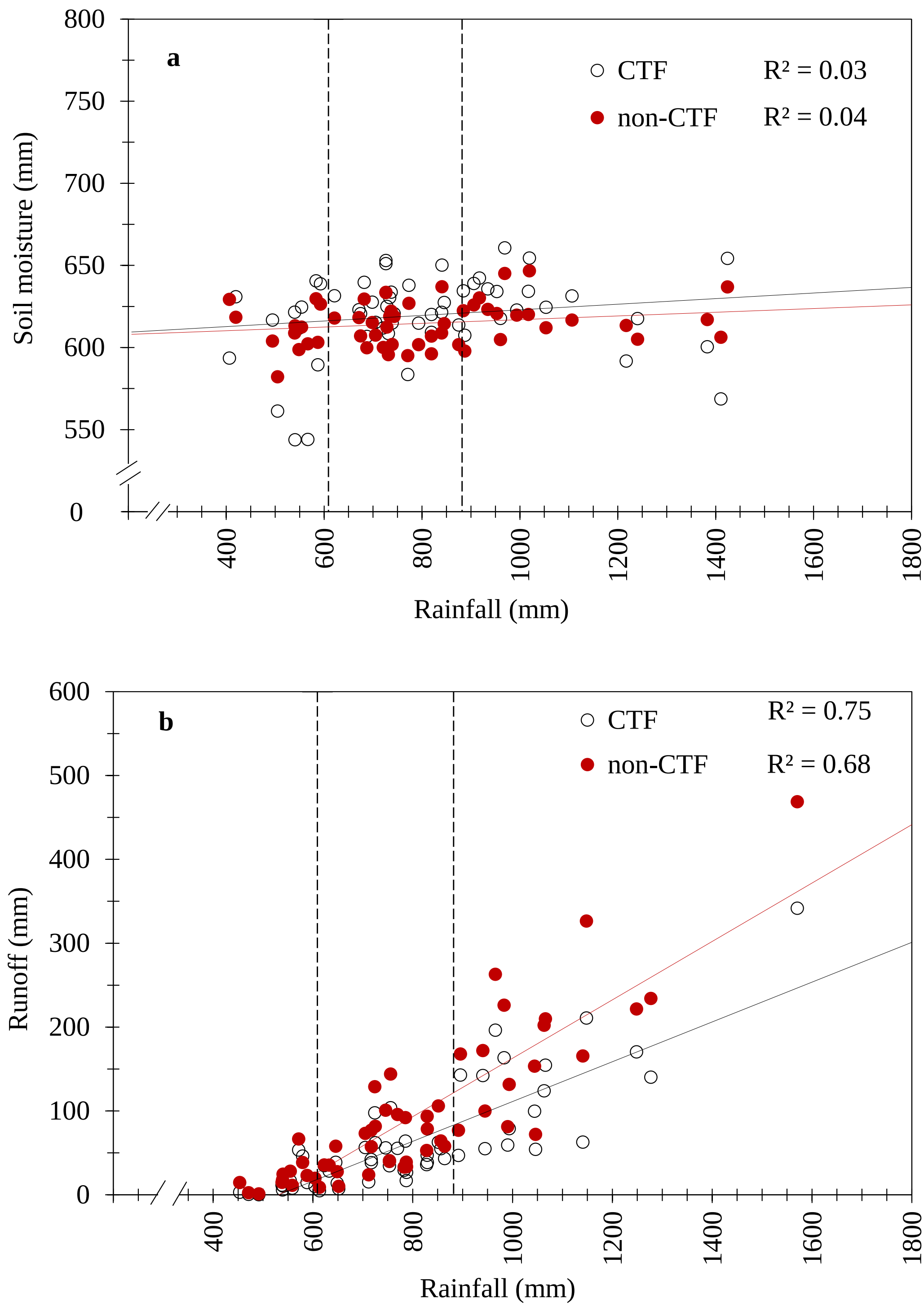

Figure 9. Soil moisture (a) and runoff (b) for 56 years of simulated sorghum-fallow cropping system on a Red Ferrosol at Toowoomba, Queensland for controlled traffic farming (CTF, black circle) and non-controlled (non-CTF, red circle) systems. Continuous lines show linear fit. Dotted vertical lines show 30th (left) and 70th (right) percentile rainfall.

Discussion

Effect of soil compaction on soil

The ability of CTF to store more water, was attributed to the greater infiltration rate (approximately double those of the non-CTF), and hydraulic conductivity (20 times higher in CTF compared to non-CTF). These results are consistent with observations reported in earlier work by Antille et al., (2016), which indicated that hydraulic conductivity was up to ten times higher in non-trafficked soil compared with trafficked soil. The ability of CTF to holding water was also emphasized by the data of modelled runoff, which was 45% higher in non-CTF system, particularly in the wetter years (>70th percentile; average rain = 590 mm/year). This attributed to the smaller size of pores and fewer natural channel in a compacted soils, which represented by non-CTF system (Fleige and Horn, 2000). Soil cone index was consistent with the soil bulk density, however, cone index samples were collected at moisture contents ranged 10-16% (w w^{-1}), which were below the optimum moisture content (21.2%) based on the Proctor test. Therefore, the cone indices were too high compared to the bulk densities. The other reason for the high cone index was suggested by Daddow and Warrington (1983), who reported that soils with a large amount of fine particles (silt and clay) will have smaller pore diameters and a higher penetration resistance at a lower bulk density than a soil with a large amount of coarse particles. Soil compaction is increasing soil bulk density and soil penetrometer resistance and decreasing soil water infiltration are signs of soil compaction (Horn et al. 1995; Hamza and Anderson 2003, 2005); which therefore, interactions of these three factors are important for crops to influence their yield and input use efficiency (Marshall and Tokunaga 2006).

Effect of soil compaction on grain yield and yield components

Field Measurements

Yield data have confirmed the existence of ‘yield reduction’ on the crop grown in a non-CTF system by up to 40% compared with CTF, which agreed with results reported by Chan et al., (2006) conducted in different soils and environment. They found that canola grain yield on the wheel track was only 34% of that recorded in between wheel tracks. The level of grain yield increase under non-compacted soil was within the range (30-55%) reported in numerous past studies (Ellington, 1986; Radford et al., 2001; Hamza and Anderson, 2003; Sadras et al., 2005). The decline in grain yield and yield components caused by compaction which was able to reduce root mass density by up to 35% (Chan et al., 2006) and that means root exploration was also reduced due to the compaction, and thus limited extraction of soil nutrients and moisture (Ahmad et al., 2009). Other study (Boone and Veen, 1994) attributed the poor agronomic performance under compacted soil to the limited supply of water, oxygen and nutrients from the soil to the root system or a limited activity of the root system. Similar findings were highlighted in the earlier study (Hussein et al., 2017) for wheat crop under the similar soil type and conditions. This study was confirmed that the impact of fertiliser formulations was not significant which was also reported in the wheat study and also highlighted by Lester et al., (2016). However, both studies found that UAN had an insignificant grain advantage, especially at 200 kg ha^{-1} N compared with ENTEC and urea. Grain yield and yield components under both traffic systems increased in the order: UAN > urea

> ENTEC, which was consistent with differences in NUE between the three fertiliser materials.

Modelling of crop performance

The modelling results suggest that soil compaction is likely to reduce crop yield and biomass on a longer-term irrespective of climate conditions, similar to those found under short-term field study. The negative effects associated with soil compaction in reducing WUE, biomass and yield, especially during below average rainfall conditions. Soil compaction reduces the sowing soil moisture, which is a key determinant of crop performance (Júnnyor et al., 2015). Successful dryland crop production especially in arid and semi-arid regions relies heavily on moisture stored at the time of sowing (Freebairn et al., 2009). Therefore, the modelled differences in this water will impact subsequent crop performance and decision-making associated with sowing (Kodur et al., 2017). Similarly, soil compaction will have negative impacts on runoff, which is due to reduced soil infiltration causing surface ponding followed by horizontal movement of water as runoff (Acuña et al., 2015; Hammer et al., 2010). As result, much of the soil water will be unavailable for crop uptake and transpiration (Hammer et al., 2010). Drier condition leads to greater reduction in yield and biomass which is due to the higher water stress (Probert et al., 1995). Whereas, during high rainfall conditions, soil moisture will be less limiting to reduce crop yield and biomass under non-CTF and CTF, although runoff will be considerably higher (Figure 9). A greater sorghum yield reduction under soil compaction is evident from Júnnyor et al., (2015), which found that but involving wheat crop grown on Vertosol soils Radford et al., (2007) and Antille et al., (2016). A higher yield reduction for wheat was as expected because it was grown under winter conditions which received lesser rainfall than the summer grown sorghum.

Economic considerations

Linear and nonlinear relationships were reported between grain yield and N application rate, however, with exception of urea under CTF system ($P<0.05$) and UAN under non-CTF ($P<0.10$), yield-to-N responses were not significant for both traffic systems and the three fertiliser formulations. The quadratic functions may be justified as all responses produced acceptable fits ($R^2 \geq 0.88$) with all fertiliser materials in both traffic systems. This appears to be a fair justifications based on the study of Sparrow (1979). Quadratic model provides a more satisfactory biological description of the relationships between yield and nitrogen application rate, and therefore may be applied regardless of non-statistical significance of the quadratic term (Shaohua et al., 1999).

The gross margins were investigated for CTF and non-CTF systems, and the tillage systems that might be used with the traffic systems were also investigated. In Australia, zero tillage (ZT) is practiced by most growers who have converted to CTF system (Tullberg, 2007), with some exceptions (Dang et al., 2017), which therefore, only ZT was considered in the assumption that made for CTF system. In contrast with non-CTF system which can also be used with shallow tillage. Given current price ratios (nitrogen-to-grain prices) that reported in Table 2, and fertiliser formulations used, gross margin penalties of AUD 75 per ha may be incurred in non-CTF systems compared with CTF when zero-tillage is practiced, and double when shallow tillage is practiced. The price of sorghum was identical among the treatments and was taken at the harvest season of 2016, which was AUD 0.23 kg^{-1}. Changes in sorghum price would affect the outcomes of gross margin due to a higher sensitivity of gross margin to the price of grain yield compared to the price of nitrogen, which was also agreed with other work conducted by Antille et al., (2017).

Conclusions

The main conclusions derived from this research are:

- Crop performance was improved in CTF conditions by up to 45% as a result of enhancing soil physical and hydraulic properties. Sorghum grain yield improvement by approximately 1300 kg ha^{-1} was possible in CTF system, which led to increased crop's gross margin by up to AUD 70 ha^{-1} when zero-tillage is practiced, and more than double when shallow tillage is practiced with CTF system in the first year of adopting this system.

- Grain yield, and crop-to-nitrogen response were more sensitive to soil compaction represented by traffic systems than fertiliser formulations, which confirmed that soil compaction is the main driver for the changes of crop-growth.

- Modelling study confirmed the positive effects associated with CTF in improving yield and biomass for longer-term conditions, and highlights that such benefits are particularly greater during drier rainfall conditions. Therefore, the greater benefits associated with CTF system are for dryland farming systems. This statement was confirmed by the data of water-use-efficiency, which was higher in the drier conditions than in the wetter, and is considered as another benefit for adopting CTF in the dryland cropping system. This is of interest because sorghum is commonly grown as dryland crop in Australia and elsewhere and any reduction is available moisture will have direct impact on crop performance.

Based on the field experiment, and the use of APSIM for simulating long-term effects of CTF adoption on crop and soil, the main benefits of CTF are enhancing agronomic performance by reducing the risk of soil compaction induced by traffic of farm machinery. Results derived from this research confirm the hypotheses formulated prior to this study and therefore are supportive of increased adoption of CTF in Southern East Queensland.

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B. Results from APSIM simulation system

Appendix B.1. Modelled results from simulated conditions of CTF for wheat

Year	Total rainfall	Seasonal rainfall	Total runoff	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1955	571	287	63	112	5507	14201	19.19
1956	1460	219	272	700	3776	11436	17.24
1957	789	235	77	91	2915	9570	12.40
1958	972	396	141	189	5489	14170	13.86
1959	1296	360	228	386	5719	15875	15.89
1960	829	200	32	287	3374	9210	16.87
1961	667	251	47	80	5744	15491	22.88
1962	1087	252	42	348	5126	13112	20.34
1963	733	191	39	131	4577	12552	23.96
1964	1116	284	107	326	5036	15249	17.73
1965	727	321	118	123	3145	9982	9.80
1966	952	332	75	183	8249	19538	24.84
1967	1097	447	186	377	3491	10519	7.81
1968	950	214	87	289	6065	16197	28.34
1969	885	470	107	103	6198	17804	13.19
1970	669	182	16	121	3954	10249	21.72
1971	1041	214	95	325	5421	14718	25.33
1972	735	157	56	124	3381	10976	21.54
1973	1289	347	120	441	5509	14157	15.87
1974	1183	328	173	324	6713	18440	20.47
1975	1103	502	85	277	6802	17674	13.55
1976	1199	282	112	562	7294	18242	25.87
1977	914	123	78	362	2756	10142	22.40
1978	1083	473	44	269	6903	18727	14.59
1979	1121	272	95	485	4781	12472	17.58
1980	599	198	42	105	4680	13238	23.64
1981	1526	271	287	534	5896	15638	21.76
1982	1174	242	76	356	6548	16835	27.06
1983	1244	616	182	396	6823	17586	11.08
1984	1160	420	98	416	5590	14293	13.31
1985	788	342	47	118	7103	17084	20.77
1986	757	229	22	148	5958	15153	26.02
1987	752	267	51	89	6650	15488	24.91
1988	1398	364	255	520	6615	17368	18.17
1989	973	189	74	285	3729	12325	19.73
1990	1069	228	116	357	4802	13943	21.06

Continue

Appendix B.1. Modelled results from simulated conditions of CTF for wheat. Below average (<30th percentile = 189 mm/season); average (246 mm/season); above average (>70th percentile=330 mm/season).

Year	Total rainfall	Seasonal rainfall	Total runoff	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1991	500	58	56	2	2269	6782	39.11
1992	805	168	36	144	4942	13498	29.42
1995	718	144	83	7	4530	11284	31.79
1996	1320	64	399	485	6052	14272	37.10
1997	752	224	54	136	4164	11101	20.23
1998	906	189	48	223	6026	13793	32.02
1999	899	165	131	140	7044	16625	25.23
2000	705	300	14	196	2475	8186	20.09
2001	935	266	142	115	3736	10559	26.48
2002	589	97	29	215	2757	9855	25.52
2003	678	316	6	33	3591	9347	11.82
2004	799	96	74	142	2799	7589	28.72
2005	546	150	13	96	3060	9304	23.94
2006	574	222	13	54	4905	12540	12.61
2007	527	317	7	45	5367	13851	9.65
2008	711	280	15	76	5527	14659	17.52
2009	757	288	44	212	3074	9399	18.64
2010	1307	271	185	253	5666	15463	20.39
2011	1350	152	298	784	6024	15206	20.22
2012	955	425	58	342	3535	9879	13.33
2013	1233	274	348	289	2414	7235	21.98
2014	668	201	101	16	2408	8359	17.59
2015	868	111	82	100	4118	10458	21.75
Mean	**932**	**256**	**101**	**245**	**4895**	**13202**	**20.9**
SD	**261.33**	**111**	**87.42**	**173.00**	**1510.39**	**3278.05**	**6.42**
Above 70%	**1250**	**330**	**179**	**422**	**5669**	**14927**	**18.80**
Average (30-70%)	**882**	**246**	**71**	**204**	**5000**	**13373**	**20.98**
Below 30%	**627**	**189**	**39**	**74**	**3879**	**10793**	**23.14**

Appendix B.2. Modelled results from simulated conditions of non-CTF for wheat

Year	Total rainfall	Total runoff	Seasonal rainfall	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1956	571	82	287	96	4803	12711	16.73
1957	1558	443	219	500	3458	9269	15.79
1958	789	118	235	76	2571	8321	10.94
1959	972	178	396	184	4853	12437	12.26
1960	1296	300	360	330	5042	14066	14.01
1961	829	51	200	288	2810	7770	14.05
1962	667	69	251	83	5052	13952	20.13
1963	1087	71	252	329	4732	11811	18.78
1964	733	42	191	140	4245	11399	22.23
1965	1116	133	284	318	4299	13095	15.14
1966	727	122	321	145	2658	8454	8.28
1967	952	126	332	170	7170	18004	21.60
1968	1097	248	447	325	2945	9131	6.59
1969	950	179	214	213	5203	15139	24.31
1970	885	136	470	105	5658	16184	12.04
1971	669	25	182	119	3375	8789	18.54
1972	1041	154	214	282	4898	12852	22.89
1973	735	66	157	131	3036	9383	19.34
1974	1289	164	347	414	4998	12851	14.40
1975	1183	238	328	275	5915	16260	18.03
1976	1103	136	502	250	6539	16932	13.02
1977	1199	206	282	448	6676	16714	23.67
1978	914	124	123	309	2434	8726	19.79
1979	1083	61	473	288	6903	18400	14.59
1980	1121	143	272	446	4092	10720	15.05
1981	599	64	198	93	4012	12226	20.26
1982	1526	362	271	475	5172	14408	19.08
1983	1174	105	242	348	5650	14678	23.35
1984	1244	261	616	347	6738	16891	10.94
1985	1160	123	420	377	4877	12727	11.61
1986	788	68	342	121	6497	15630	19.00
1987	757	28	229	145	5178	14019	22.61
1988	752	60	267	102	5755	14460	21.55
1989	1398	303	364	484	6511	16548	17.89
1990	973	104	189	264	3219	11169	17.03
1991	1069	168	228	321	4161	12318	18.25
1992	500	69	425	10	2018	5866	16.73
1993	805	51	274	143	4376	12069	15.79
1996	718	123	201	95	3851	9747	10.94

Continue

Appendix B.2. Modelled results from simulated conditions of non-CTF for wheat. Below average (<30th percentile = 189 mm/season); average (246 mm/season); above average (>70th percentile=330 mm/season).

Year	Total rainfall	Seasonal rainfall	Total runoff	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1997	1423	58	543	360	5307	12510	34.80
1998	752	168	76	134	3454	9613	26.05
1999	906	144	74	224	5348	12006	31.25
2000	899	64	164	122	6326	15242	0.00
2001	705	224	19	202	2168	7121	17.19
2002	935	189	184	107	3129	9013	28.08
2003	589	165	38	210	2472	8623	20.93
2005	799	300	139	214	2119	6086	17.83
2006	546	266	23	100	2583	7776	23.78
2007	574	97	24	81	4320	11061	22.35
2008	527	316	11	13	4902	12348	9.90
2009	711	96	30	88	4828	13237	25.75
2010	757	150	69	200	2748	8396	0.00
2011	1307	222	221	249	5417	14410	9.54
2012	1590	317	441	631	5254	13111	8.15
2013	955	280	80	332	3069	8522	15.43
2014	1233	288	429	228	2143	6161	17.02
2015	668	271	121	29	1774	5116	17.82
2016	868	152	97	106	2996	8134	18.08
Mean	**940**	**256**	**141**	**225**	**4284**	**11604**	**17.53**
SD	**276.03**	**111**	**117.72**	**138.44**	**1553.88**	**3653.74**	**6**
Above 70%	**1250**	**330**	**243**	**371**	**5133**	**13468**	**16.87**
Average (30-70%)	**882**	**246**	**104**	**192**	**4362**	**11864**	**18.22**
Below 30%	**627**	**189**	**47**	**87**	**3057**	**8543**	**17.24**

Appendix B.3. Modelled results from simulated conditions of CTF for sorghum

Year	Total rainfall	Seasonal rainfall	Total runoff	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1956	1597	387	364	355	3055	8450	3.83
1957	964	242	77	476	3143	8572	8.13
1958	500	701	6	27	3186	8063	13.15
1959	1220	665	147	345	2918	7694	4.16
1960	981	408	78	379	3105	8642	4.67
1961	613	551	5	104	2899	8688	7.11
1962	864	318	43	284	2833	7770	5.14
1963	652	448	7	152	2699	7934	8.48
1964	828	318	36	241	3067	8124	6.85
1965	787	348	17	246	3567	9643	11.23
1966	756	434	104	93	3024	8468	8.70
1967	892	444	47	219	3032	8368	6.99
1968	1063	273	124	432	2783	7892	6.27
1969	649	355	14	154	3415	8803	12.50
1970	770	728	55	66	3266	8496	9.19
1971	993	440	79	219	2619	6925	3.60
1972	705	590	56	216	2870	8010	6.53
1973	829	617	38	216	2901	8076	4.91
1974	1044	426	100	405	2866	7902	4.64
1975	754	834	35	177	3160	8560	7.42
1976	1249	384	170	439	2648	7745	3.17
1977	783	373	29	264	3334	8647	8.67
1978	717	430	38	128	3043	7903	8.16
1979	945	338	55	264	3087	8402	7.17
1980	754	738	41	202	3247	8171	9.60
1981	983	571	163	100	2991	8523	4.05
1982	1046	204	54	486	2906	7638	5.09
1983	538	462	12	143	3320	8861	16.30
1984	1277	338	140	376	2907	8344	6.30
1985	829	401	47	271	3344	8634	9.91
1986	856	233	55	93	3337	8853	8.33
1987	559	633	8	65	3260	8065	14.00
1988	941	364	142	58	3454	9160	5.45
1989	1141	479	63	581	3025	8474	8.32
1990	990	332	59	340	3253	8735	6.79
1991	786	470	64	180	2947	7936	8.86
1992	633	191	28	62	3260	8231	6.93
1993	492	311	0	99	3237	8493	16.95
1994	540	387	11	0	2907	8323	9.34

Continue

Appendix B.3. Modelled results from simulated conditions of CTF for sorghum. Below average (<30th percentile = 386 mm/season); average (390 mm/season); above average (>70th percentile=590 mm/season).

Year	Total rainfall	Seasonal Rainfall	Total runoff	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1995	572	316	53	15	2926	7954	9.25
1996	896	707	143	218	3317	9102	4.69
1997	1148	474	211	330	3315	9153	6.99
1998	623	377	35	206	3302	8326	8.76
1999	1066	509	154	238	3250	8455	6.39
2000	712	381	15	191	3122	9128	8.20
2001	724	512	98	120	3357	8695	6.56
2002	580	386	46	139	3408	8562	8.83
2003	646	295	39	75	3453	8954	11.69
2004	852	408	63	176	3230	8262	7.92
2005	589	322	15	104	3257	8791	10.11
2006	555	328	16	94	3386	8501	10.32
2007	539	196	6	0	3021	8190	15.44
2008	471	263	0	0	2639	7214	10.04
2009	604	329	10	30	3028	8090	9.20
2010	454	195	3	1	3020	7789	15.49
2011	1571	1022	342	590	2824	7909	2.76
2012	788	386	27	228	2903	8217	7.53
2013	966	578	196	182	3336	8788	5.77
2014	717	188	42	292	3344	9061	17.77
2015	746	380	56	102	2939	7627	7.73
2016	725	374	62	83	3114	8532	8.33
Mean	**821**	**423**	**70**	**203**	**3105**	**8353**	**8.44**
SD	**248.52**	**168**	**73.83**	**144.53**	**225.69**	**495.83**	**3**
Above 70%	**1277**	**590**	**185**	**463**	**3137**	**8379**	**5.51**
Average (30-70%)	**882**	**390**	**75**	**222**	**3111**	**8347**	**7.00**
Below 30%	**609**	**386**	**26**	**103**	**2944**	**8325**	**10.68**

Appendix B.4. Modelled results from simulated conditions of non-CTF for sorghum

Year	Total rainfall	Seasonal rainfall	Total runoff	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1956	1597	387	509	729	1966	5431	4.36
1957	964	242	106	290	1688	4468	2.70
1958	500	701	14	127	660	1773	2.87
1959	1220	665	239	367	2015	5420	3.48
1960	981	408	103	364	2313	6505	6.64
1961	613	551	9	146	2706	7998	4.21
1962	864	318	58	330	2319	6316	4.05
1963	652	448	10	224	1290	3802	3.95
1964	828	318	53	240	1768	4904	8.34
1965	787	348	39	299	2649	7328	5.02
1966	756	434	144	115	1794	5291	4.56
1967	892	444	77	286	1978	5539	3.83
1968	1063	273	202	414	1698	4864	3.56
1969	649	355	28	188	973	3379	3.67
1970	770	728	96	152	1304	3585	2.21
1971	993	440	132	273	1606	4347	4.29
1972	705	590	73	237	1886	5242	2.59
1973	829	617	78	226	1527	4485	3.50
1974	1044	426	153	408	2160	5979	5.75
1975	754	834	41	197	2447	6729	2.59
1976	1249	384	222	434	2158	6411	7.78
1977	783	373	33	256	2991	7782	3.40
1978	717	430	57	244	1267	3523	5.99
1979	945	338	100	260	2577	7110	8.12
1980	754	738	40	219	2746	6869	3.52
1981	983	571	226	241	2596	7334	4.73
1982	1046	204	72	477	2700	7069	5.92
1983	538	462	15	195	1205	3620	3.19
1984	1277	338	234	389	1471	4368	6.12
1985	829	401	93	250	2065	5584	7.16
1986	856	233	64	179	2871	7516	7.11
1987	559	633	11	98	1655	4266	3.77
1988	941	364	172	171	2527	6841	6.88
1989	1141	479	166	488	2502	6901	6.12
1990	990	332	81	377	2931	7824	2.99
1991	786	470	92	222	1068	2907	5.39
1992	633	191	35	202	2536	6534	5.38
1993	492	311	1	116	1039	2925	6.78
1994	540	387	25	119	2112	6107	4.36

Continue

Appendix B.4. Modelled results from simulated conditions of non-CTF for sorghum. Below average (<30th percentile = 386 mm/season); average (390 mm/season); above average (>70th percentile=590 mm/season).

Year	Total rainfall	Seasonal Rainfall	Total runoff	Total drain	Yield	Biomass	WUE
	(mm)	(mm)	(mm)	(mm)	(kg ha^{-1})	(kg ha^{-1})	(Kg ha^{-1} mm^{-1})
1995	572	316	67	190	1514	4137	4.78
1996	896	707	168	279	3120	8590	4.41
1997	1148	474	326	262	2516	6953	5.31
1998	623	377	36	236	2580	6602	6.84
1999	1066	509	210	300	1668	4275	3.28
2000	712	381	24	195	2790	8190	7.33
2001	724	512	129	165	2634	6669	5.15
2002	580	386	39	174	1815	4627	4.70
2003	646	295	58	169	821	2690	2.78
2004	852	408	106	252	758	2069	1.86
2005	589	322	23	170	935	2686	2.90
2006	555	328	28	131	1174	3273	3.58
2007	539	196	18	88	921	3120	4.71
2008	471	263	2	70	1755	4850	6.68
2009	604	329	20	108	2111	5660	6.42
2010	454	195	15	79	797	2199	2.80
2011	1571	1022	469	554	2647	7363	2.59
2012	788	386	33	276	1707	4848	4.43
2013	966	578	263	207	1411	3943	2.44
2014	717	188	77	258	1567	4196	8.33
2015	746	380	101	193	1538	3967	4.04
2016	725	374	82	124	2140	5960	5.72
Mean	**821**	**423**	**102**	**246**	**1913**	**5274**	**4.82**
SD	**248.52**	**168**	**103.64**	**123.02**	**657.37**	**1729.51**	**2**
Above 70%	**1277**	**590**	**283**	**426**	**2259**	**6399**	**4.11**
Average (30-70%)	**882**	**390**	**108**	**263**	**2093**	**5700**	**4.61**
Below 30%	**609**	**386**	**37**	**164**	**1676**	**4677**	**5.22**

C. Regression analyses

C.1. Wheat

C.1.1. Regression analysis - Yield to N response relationships (UAN) for wheat (CTF)

Linear

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.768	.590	.385	322.809

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	300100.500	1	300100.500	2.880	.232
Residual	208411.207	2	104205.604		
Total	508511.707	3			
The independent variable is N Rate					

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	2.450	1.444	.768	1.697	.232
(Constant)	2907.290	270.081		10.764	.009

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.996	.992	.975	65.137

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	504268.923	2	252134.461	59.427	.091
Residual	4242.784	1	4242.784		
Total	508511.707	3			
The independent variable is N Rate					

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	9.228	1.020	2.894	9.051	.070
N Rate ** 2	-.023	.003	-2.218	-6.937	.091
(Constant)	2681.365	63.487		42.235	.015

C.1.2. Regression analysis - Yield to N response relationships (ENTEC) for wheat (CTF)

Linear

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.967	.936	.904	113.600

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	375434.802	1	375434.802	29.092	.033
Residual	25809.768	2	12904.884		
Total	401244.570	3			
The independent variable is N Rate					

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	2.740	.508	.967	5.394	.033
(Constant)	2742.020	95.044		28.850	.001

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.999	.999	.997	20.035

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	400843.162	2	200421.581	499.296	.032
Residual	401.408	1	401.408		
Total	401244.570	3			
The independent variable is N Rate					

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	5.131	.314	1.811	16.362	.039
N Rate ** 2	-.008	.001	-.881	-7.956	.080
(Constant)	2662.320	19.528		136.334	.005

C.1.3. Regression analysis - Yield to N response relationships (urea) for wheat (CTF)

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.320	.102	-.346	382.857

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	33423.488	1	33423.488	.228	.680
Residual	293158.332	2	146579.166		
Total	326581.820	3			

The independent variable is N Rate

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	.818	1.712	.320	.478	.680
(Constant)	2957.260	320.321		9.232	.012

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.979	.958	.875	116.767

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	312947.178	2	156473.589	11.476	.204
Residual	13634.642	1	13634.642		
Total	326581.820	3			

The independent variable is N Rate

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	8.748	1.828	3.423	4.786	.131
N Rate ** 2	-.026	.006	-3.238	-4.528	.138
(Constant)	2692.910	113.811		23.661	.027

C.1.4. Regression analysis - Yield to N response relationships (UAN) for wheat (Non-CTF)

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.473	.224	-.164	424.596

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	104040.312	1	104040.312	.577	.527
Residual	360562.875	2	180281.438		
Total	464603.188	3			

The independent variable is N Rate

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	1.443	1.899	.473	.760	.527
(Constant)	2597.500	355.242		7.312	.018

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.889	.790	.369	312.490

The independent variable is N Rate

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	366952.875	2	183476.438	1.879	.458
Residual	97650.312	1	97650.312		
Total	464603.188	3			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	9.134	4.891	2.996	1.867	.313
N Rate ** 2	-.026	.016	-2.633	-1.641	.348
(Constant)	2341.125	304.578		7.686	.082

C.1.5. Regression analysis - Yield to N response relationships (ENTEC) for wheat (Non-CTF)

Linear

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.813	.661	.492	218.692
The independent variable is N Rate			

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	186766.464	1	186766.464	3.905	.187
Residual	95652.603	2	47826.302		
Total	282419.067	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	1.933	.978	.813	1.976	.187
(Constant)	2504.270	182.971		13.687	.005

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.950	.902	.707	166.162
The independent variable is N Rate			

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	254809.187	2	127404.593	4.614	.313
Residual	27609.881	1	27609.881		
Total	282419.067	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	5.845	2.601	2.460	2.248	.267
N Rate ** 2	-.013	.008	-1.718	-1.570	.361
(Constant)	2373.845	161.955		14.657	.043

C.1.6. Regression analysis - Yield to N response relationships (urea) for wheat (Non-CTF)

Linear

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.963	.928	.892	93.819
The independent variable is N Rate			

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	226802.402	1	226802.402	25.767	.037
Residual	17604.138	2	8802.069		
Total	244406.540	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	2.130	.420	.963	5.076	.037
(Constant)	2483.330	78.495		31.637	.001

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.996	.993	.978	42.172
The independent variable is N Rate			

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	242628.042	2	121314.021	68.21 2	.085
Residual	1778.498	1	1778.498		
Total	244406.540	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	4.017	.660	1.817	6.085	.104
N Rate ** 2	-.006	.002	-.891	-2.983	.206
(Constant)	2420.430	41.104		58.885	.011

C.2. Sorghum

C.2.1. Regression analysis - Yield to N response relationships (UAN) for sorghum(CTF)

Linear

Model Summary						
R	R Square	Adjusted R Square	Std. Error of the Estimate			
.450	.203	-.196	1151.186			
The independent variable is N Rate						

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	673224.818	1	673224.818	.508	.550
Residual	2650458.497	2	1325229.248		
Total	3323683.315	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	3.669	5.148	.450	.713	.550
(Constant)	2335.555	963.151		2.425	.136

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.994	.988	.964	200.978
The independent variable is N Rate			

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	3283291.243	2	1641645.621	40.643	.110
Residual	40392.072	1	40392.072		
Total	3323683.315	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	27.903	3.146	3.422	8.870	.071
N Rate ** 2	-.081	.010	-3.102	-8.039	.079
(Constant)	1527.770	195.889		7.799	.081

C.2.2. Regression analysis - Yield to N response relationships (ENTEC) for sorghum (CTF)

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.624	.389	.083	666.741

The independent variable is N Rate

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	565750.794	1	565750.794	1.273	.376
Residual	889087.607	2	444543.803		
Total	1454838.401	3			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	3.364	2.982	.624	1.128	.376
(Constant)	1999.023	557.836		3.584	.070

Quadratic

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.940	.883	.650	412.188

The independent variable is N Rate

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1284939.597	2	642469.798	3.781	.342
Residual	169898.804	1	169898.804		
Total	1454838.401	3			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	16.085	6.452	2.982	2.493	.243
N Rate ** 2	-.042	.021	-2.461	-2.057	.288
(Constant)	1574.998	401.751		3.920	.159

C.2.3. Regression analysis - Yield to N response relationships (urea) for sorghum (CTF)

Linear

Model Summary						
R	R Square	Adjusted R Square	Std. Error of the Estimate			
.308	.095	-.358	1012.010			
The independent variable is N Rate						
ANOVA						
	Sum of Squares	df	Mean Square	F	Sig.	
Regression	214617.762	1	214617.762	.210	.692	
Residual	2048329.178	2	1024164.589			
Total	2262946.940	3				
Coefficients						
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	
	B	Std. Error	Beta			
N Rate	2.072	4.526	.308	.458	.692	
(Constant)	2203.660	846.708		2.603	.121	

Quadratic

Model Summary						
R	R Square	Adjusted R Square	Std. Error of the Estimate			
1.000	1.000	.999	23.836			
The independent variable is N Rate						
ANOVA						
	Sum of Squares	df	Mean Square	F	Sig.	
Regression	2262378.762	2	1131189.381	1990.907	.016	
Residual	568.178	1	568.178			
Total	2262946.940	3				
Coefficients						
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	
	B	Std. Error	Beta			
N Rate	23.537	.373	3.499	63.084	.010	
N Rate ** 2	-.072	.001	-3.329	-60.034	.011	
(Constant)	1488.160	23.233		64.054	.010	

C.2.4. Regression analysis - Yield to N response relationships (UAN) for sorghum (Non-CTF)

Linear

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.128	.016	-.475	612.570
The independent variable is N Rate			

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	12587.653	1	12587.653	.034	.872
Residual	750483.756	2	375241.878		
Total	763071.409	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	.502	2.739	.128	.183	.872
(Constant)	1460.820	512.513		2.850	.104

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.997	.994	.981	69.217
The independent variable is N Rate			

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	758280.349	2	379140.175	79.135	.079
Residual	4791.060	1	4791.060		
Total	763071.409	3			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	13.455	1.083	3.444	12.419	.051
N Rate ** 2	-.043	.003	-3.460	-12.476	.051
(Constant)	1029.052	67.465		15.253	.042

C.2.5. Regression analysis - Yield to N response relationships (ENTEC) for sorghum (Non-CTF)

Linear

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.273	.074	-.389	333.106

The independent variable is N Rate

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	17811.496	1	17811.496	.161	.727
Residual	221919.880	2	110959.940		
Total	239731.376	3			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N_Rate	.597	1.490	.273	.401	.727
(Constant)	1294.480	278.697		4.645	.043

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.987	.974	.921	79.570

The independent variable is N Rate

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	233399.915	2	116699.958	18.432	.163
Residual	6331.461	1	6331.461		
Total	239731.376	3			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	7.562	1.245	3.453	6.071	.104
N Rate ** 2	-.023	.004	-3.319	-5.835	.108
(Constant)	1062.322	77.556		13.698	.046

C.2.6. Regression analysis - Yield to N response relationships (urea) for sorghum (Non-CTF)

Linear

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.136	.019	-.472	520.986

The independent variable is N Rate

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	10270.872	1	10270.872	.038	.864
Residual	542853.041	2	271426.520		
Total	553123.912	3			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	.453	2.330	.136	.195	.864
(Constant)	1432.223	435.888		3.286	.081

Quadratic

Model Summary			
R	R Square	Adjusted R Square	Std. Error of the Estimate
.991	.981	.943	102.258

The independent variable is N Rate

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	542667.291	2	271333.645	25.948	.137
Residual	10456.622	1	10456.622		
Total	553123.912	3			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
N Rate	11.398	1.601	3.427	7.121	.089
N Rate ** 2	-.036	.005	-3.434	-7.135	.089
(Constant)	1067.395	99.668		10.709	.059