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Controlled traffic farming effects on productivity of grain sorghum, rainfall and fertiliser nitrogen use efficiency

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A R T I C L E I N F O

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A B S T R A C T

Controlled traffic farming (CTF) is a mechanisation system in which all machinery has the same (or modular) working and track width so that field traffic can be confined to the least possible area of permanent traffic lanes. CTF enables productivity of non-compacted crop beds to be optimised for given energy, fertiliser and water (rainfall) inputs. This study investigated the agronomic response and economic return of grain sorghum grown in compacted and non-compacted soils to represent the conditions of non-CTF and CTF systems, respectively. Yield-to-nitrogen (N) responses were derived following application of urea, 3,4-dimethyl pyrazole phosphate-treated urea (DMPP), and urea ammonium nitrate (UAN, 32% N) at rates between 0 and 300 kg ha^{-1} N. Selected soil properties were measured to guide parametrisation of the Agricultural Production Systems Simulator (APSIM), which was used to assess long-term (55 years) effects of CTF and non-CTF soil conditions on crop productivity, rainfall use efficiency (RUE) and develop rainfall-runoff relationships. Grain yield and yield components (harvest Index, grain thousand-grain weight, number of grains) were significantly higher in CTF compared with non-CTF. On average, the most economic N rates, and corresponding grain yields, were 144 and 3428 kg ha^{-1}, and 100 and 1796 kg ha^{-1} for CTF and non-CTF, respectively. When N inputs were optimised, agronomic efficiency calculations showed 18% increase in CTF compared with non-CTF. Nitrogen use efficiency (NUE) was 1.75 times higher in CTF than in non-CTF. Rainfall-use efficiency was about 65% higher in CTF, which concurrently reduced the amount of runoff compared with non-CTF. Average rainfall season (330–450 mm in-crop) grain yield was 30% lower in non-CTF compared with CTF. For subtropical conditions of Australia, long-term APSIM simulations showed that increased productivity and inter-season yield stability can increase gross margin of grain sorghum by AUD74 ha^{-1} or greater depending on the adopted tillage system and in-crop rainfall. In non-CTF systems, improvements in NUE and RUE are constrained by soil compaction. Enhanced efficiency fertilisers, such as DMPP-treated urea, cannot compensate for other stresses caused by soil compaction and therefore cannot achieve the same NUE and RUE as the CTF system. Adoption of CTF delivers improved resource-use efficiency and profitability in rainfall-limited environments.

1. Introduction

Compaction adversely affects the physical and hydraulic properties of agricultural soils, and the ability of crops to efficiently use water (rainfall, irrigation) and applied nutrients, thus reducing fertiliser recovery in grain [2]. Compaction is also associated with processes such as erosion and runoff as it affects water infiltration into soil, and water retention and transmission within the soil [3]. These effects can have off-farm environmental impacts such as increased risk of diffuse pollution [4,5] and greenhouse gas emissions [6,7], and significantly reduce plant available water capacity (PAWC) [8]. These are important considerations for dryland cropping systems that rely on rainfall and soil water conservation for successful crop establishment [9]. Compaction is often persistent, particularly in the subsoil, and its alleviation through tillage is both energy-demanding and transient [10].

Controlled traffic farming (CTF) is an effective solution to manage compaction by confining all load-bearing wheels to permanent traffic lanes; thus, optimising productivity of non-compacted crop beds for given energy, fertiliser and water inputs [11]. The Australian Controlled

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Nomenclature

AE	agronomic efficiency (kg kg^{-1}), determined by the difference method
APSIM	Agricultural Production Systems Simulator (https://www.apsim.info/)
AUD	Australian dollar (AUD1 ≈ USD0.75)
CN	runoff curve number
CTF	controlled traffic farming; non-CTF, non-controlled traffic farming
DMPP	3,4-dimethyl pyrazole phosphate-treated urea (commercially known in Australia as ENTEC®, 46% N)
DUL	drained upper limit (field capacity) [1]
EEF	enhanced efficiency fertilisers
GI	gross income (AUD ha^{-1})
GM	gross margin (AUD ha^{-1})
HI	harvest Index (%)
LL	crop lower limit (wilting point) [1]
MERN	most economic rate of nitrogen (kg ha^{-1} N)
NUE	nitrogen (N) use efficiency, expressed as apparent N recovery in grain (%)
PAWC	plant available water capacity [1]
PSA	particle size analysis
RUE	rainfall use efficiency
SAT	soil water content at saturation [1]
SD	standard deviation
ST	shallow tillage (less than 200 mm deep)
TG_N	total nitrogen in grain (%, w/w)
TGW	thousand-grain weight (g)
TVC	total variable costs (AUD ha^{-1})
UAN	urea-ammonium nitrate (32% N, solution)
ZT	zero-tillage

Traffic Farming Association Inc. (ACTFA, https://www.actfa.net/controlled-traffic-farming/) defines CTF as a system in which: (1) all machinery has the same or modular working and track width so that field traffic can be confined to the least possible area of permanent traffic lanes, (2) all machinery is capable of precise guidance along permanent traffic lanes, and (3) the layout of permanent traffic lanes is designed to optimise surface drainage and operational logistics [6].

In Australian grain cropping systems, the cost of soil compaction, determined as equivalent production loss, is estimated to be more than AUD1 billion per year. Yield penalties are often between 10% and 30% occurring in approximately 67% of years, and the total cost of lost production is higher than that of sodicity, which is estimated at ≈ AUD600M per year [12,13]. Crop responses to the avoidance of traffic compaction in CTF systems are reported to be invariably positive compared with non-CTF systems, and with significantly more reliability and less inter-annual yield variability [6,14,15]. Research and on-farm practice [16,17] have both shown increased opportunities for establishment of double-crops and inter-cropping under CTF, which arise from improved water economy in rainfall-limited environments. In dryland cropping systems with seasonal rainfall, such as those of Australia's northern grain region,[1] this is recognised as a major economic benefit of CTF compared with non-CTF systems. Without CTF, the frequency of successful crops in this region is reported to be 0.7 crops per year (or less) for conventional tillage and about 1 crop per year for zero-tillage systems, but it can increase to 1.2 crops per year or greater when zero-tillage is jointly practiced with CTF [18]. A recent study by Hussein et al. [19] under rainfed conditions has shown that CTF systems have 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 other studies, which have shown improved structural conditions in soils established under CTF (e.g., McHugh et al. [20] in southern Queensland, Australia; Millington et al. [21] in the West Midlands of England) and by enhanced nutrient uptake in the absence of traffic compaction [22]. Co-limitation of soil water and nitrogen (N) uptake by the crop due, for example, to soil physico-mechanical constraints, affects yield potential [23] and consequently the agronomic efficiency of N applied as fertiliser. The agronomic effectiveness of different N fertiliser formulations, including enhanced efficiency fertilisers, and their role in mitigating N losses is well documented [25,26]. However, much of the past research has given little or no consideration to the detrimental effect of traffic compaction on N use efficiency (NUE), with some exceptions [e.g., 27, 28], but all this earlier work has not been conducted in the context of CTF systems. Hussein et al. [19]'s study on wheat (*Triticum aestivum* L.) showed that in non-CTF systems, improvements in NUE are constrained by compaction and compaction-induced effects on soil water. Enhanced efficiency fertilisers (EEF) alone cannot compensate for other stresses caused by compaction and therefore cannot achieve the same NUE that may be possible in a CTF system.

The work reported in this article expands Hussein et al. [19]'s investigation, which explored traffic compaction effects on yield-to-N response relationships, and N and (water) rainfall use efficiency (RUE) of winter cereal crops, by focusing on grain sorghum (*Sorghum bicolor* L., Moench). The increased cropping frequency that is possible in rainfed CTF systems enables grain sorghum to be grown in rotation with winter cereals; thus, the relevance of the study reported herein. Sorghum has moderate susceptibility to soil compaction, as shown by Searcy et al. [29], and is therefore likely to be responsive to CTF. Other than Hussein's work on wheat there appears to be a paucity of detailed studies in the scientific literature comparing the effects of CTF and non-CTF on the yield-to-N response relationships under subtropical edapho-climatic conditions, and the implications for NUE and RUE of summer crops. Since CTF is practiced in Australia in approximately 40% of the land used for grain cropping (ACTFA, https://www.actfa.net/), these are important considerations at national-level and are also relevant to broadacre cropping elsewhere. The grain industry is committed to closing yield gaps of major rainfed crops (wheat, barley, sorghum, canola) grown in Australia ([30]; Yield Gap Australia: http://yieldgapaustralia.com.au/) as a means to increase NUE and RUE without any impact on profitability. Achieving sustained productivity increases requires identification, and subsequent adoption by growers, of economically-viable management practices [31]. Therefore, this work seeks to demonstrate the potential of CTF to increase productivity, NUE and RUE of grain sorghum in agreement with the industry's aspirations of narrowing yield gaps and the expectation that this must be achieved without increasing the environmental footprint of arable cropping. Further, the dataset reported here is relevant to other industries (e.g., cotton, sugar), which are committed to reducing the environmental impact associated with fertiliser and water-use by crops, as outlined in the objectives of the Australian Government's More Profit from Nitrogen Program (http://www.crdc.com.au/more-profit-nitrogen) [32].

The work reported in this article takes a system's view on possible limitations on improving NUE and RUE in rainfed cropping when soil is affected by compaction. A 55-year climatic dataset (1960–2015) was collated and combined with soil and crop data collected from field measurements to guide parametrisation and application of the

[1] Encompasses central and southern Queensland (QLD) and northern New South Wales (NSW) and has tropical, subtropical and temperate environments. Summer dominant cropping in QLD and winter dominant in NSW. Relatively high yield potential, but also high variability depending on in-crop rainfall. Stored soil water at sowing significantly increases yield reliability [24].

Agricultural Production Systems Simulator (APSIM) [33]. The APSIM model was used to assess the likely effects of changed soil conditions, due to compaction, on crop productivity, RUE and runoff. Simulations were conducted with soil physical, hydraulic and mechanical properties representing conditions of CTF and non-CTF systems to assist with the interpretation and generalisation of experimental observations.

2. Objectives

The objectives of this study were to: (1) determine the effects of CTF and non-CTF management on the yield-to-nitrogen response relationship of grain sorghum for a range of N fertiliser formulations, which includes conventional and enhanced efficiency fertilisers, (2) determine the effect of traffic compaction on RUE and fertiliser NUE to be able to quantify differences between CTF and non-CTF, and (3) parametrise APSIM to help interpret and generalise the experimental findings by: (*a*) developing relationships that capture the effects of N fertilisation and traffic compaction on yield and crop biomass, RUE and runoff as a function of in-crop rainfall, and (*b*) conducting technical-economic analyses to quantify the effects of traffic-induced soil compaction on crop gross margin, economic return from fertiliser used on crop, and assess the most economic rate of N for the two traffic systems.

3. Materials and methods

3.1. *Experimental site*

The experiment was conducted at the research station (27°36′35.70″S, 151°55′49.38″E, elevation: 692-m above-sea-level) of the Centre for Agricultural Engineering at the University of Southern Queensland in Toowoomba (Australia) during the 2015–2016 crop summer season. Rainfall and temperature records for the experimental site are shown in Fig. 1. Overall, mean air temperatures did not depart significantly from long-term records (1960–2015). Monthly rainfall was similar to long-term records in the earlier part of the season (October–December 2015), but cumulative rainfall between January and March 2016 was about 40% lower than long-term records for the same period.

The soil at the site is a Red Ferrosol (Oxisol in the NRCS-USDA Soil Taxonomy) and is commonly used in Queensland for grain cropping [35]. The soil is moderately well-drained and has a gentle, uniform slope (<0.5%). Soil textural analyses [36] for the bulked 0–200 mm layer reported 69% clay, 11% silt and 20% sand, and 68% clay, 6% silt and 26% sand for the bulked 200–500 mm depth interval, respectively. Clay, silt and sand comprise of the following fractions: <0.002 mm, 0.002–0.02 mm, and 0.02–2 mm, respectively. Soil $pH_{1:5}$ and electrical conductivity of soil ($EC_{1:5}$) were 6.22 and 0.07 dS m^{-1}, respectively [37]. The previous crop established at the site (winter of 2015) was wheat (*Triticum aestivum* L. *cv*. Summate).

The experiment was conducted in two adjacent blocks; namely: CTF and non-CTF, respectively, in which 60 plots (dimensions: 4-m × 5-m) with 4 plant rows per plot were laid-out in a completely randomised design, and subject to the fertiliser treatments described here. There was a requirement for historical compaction to be removed to enable the two traffic treatments (CTF and non-CTF, respectively) to be imposed [38]. For this, the soil was first subsoiled to a depth of 300 mm and a powered rotary harrow was then used to smooth and level-off the surface. No further operations were conducted in soil representing the CTF system, but 9 adjacent wheel-beside-wheel passes of a Belarus 920 tractor, operated at 5 km h^{-1} (front tyres: 11.2–20 at 0.20 MPa; rear tyres: 18.4R30 at 0.10 MPa), were applied after soil cultivation to represent random traffic of the non-CTF plots. This operation resulted in about 13% higher soil bulk density in non-CTF compared with CTF plots, consistent with increments in density induced by grain harvesting equipment traffic on soil not affected by compaction [39,40]. Given that the tractor used in these experiments was lighter than other farm vehicles commonly used in grain production systems in Australia, the required increase in density in non-CTF plots was achieved by performing multiple passes [41]. Mean ± standard deviation (SD) soil water contents at the time the tractor passes were imposed were 11.36% ± 2.06% (w/w) and 15.25% ± 2.36% (w/w) at the 0–200 mm and 200–500 mm depth intervals, respectively. Soil cultivation prior to establishing the experiments at the site, and subsequent traffic on non-CTF plots, ensured uniform soil conditions (density and strength) were achieved within-traffic treatments. This, in turn, ensured fertiliser × compaction treatments were unaffected by any pre-existing soil mechanical condition.

Grain sorghum (*cv*. Pioneer G22) was sown on November 11, 2015 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 a 750-mm row-spacing, and the target population was 50,000 plants per ha. Three types of fertiliser were used; namely: urea (46% N), urea treated with the nitrification inhibitor 3,4-dimethyl pyrazole phosphate (DMPP),

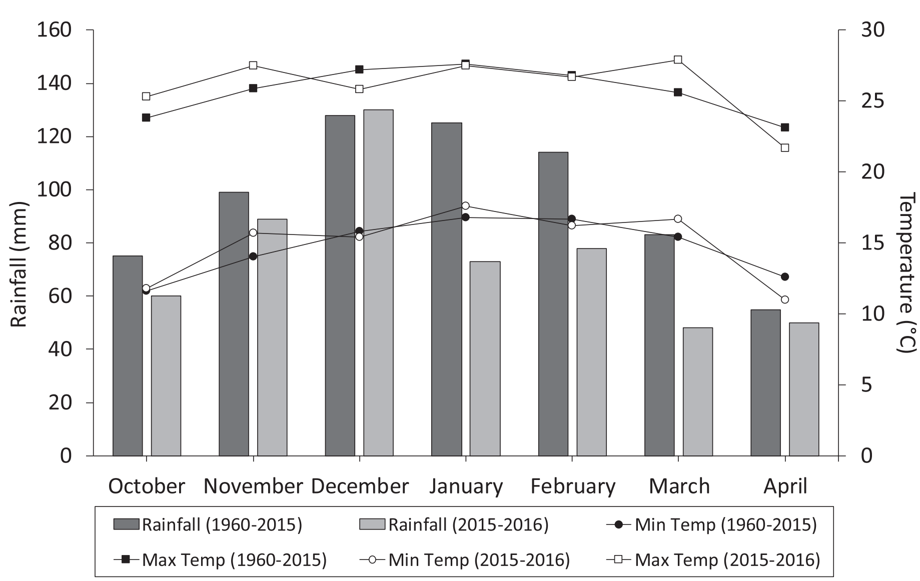

Fig. 1. Monthly rainfall (mm), maximum and minimum temperatures for the 2015–2016 summer season and long-term (1960–2015) seasonal records for Toowoomba, Queensland, Australia (after [34]).

commercially known as ENTEC® urea (46% N), and urea ammonium nitrate referred to as UAN (32% N, solution). The use of DMPP in Australia has gained attention because of its potential to reduce denitrification losses [42]. Fertilisers were hand-applied in a single band next to the plant row and incorporated to a depth of ≈50 mm at field equivalent rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1} N. For the plots that received 100 kg ha^{-1} N, the full N rate was applied on November 30, 2015. For the plots that received 200 and 300 kg ha^{-1} N, the full N rate was halved, and the splits applied on November 30, 2015 and December 11, 2015, respectively. All fertiliser treatments, including controls, were setup in triplicate ($n = 3$). A summary of the experimental design is given below:

- 3 fertiliser types (urea, DMPP-treated urea, urea ammonium nitrate) × 3 fertiliser levels (100, 200, 300 kg ha^{-1} N) × 3 replicates plus 3 control plots without fertiliser: 30 plots.
- 2 traffic treatments (CTF and non-CTF).
- Total number of plots: 30 × 2 = 60.

3.2. Soil physical properties

Soil bulk density (ρ_b) was determined for the 0–300 mm depth layer at increments of 150 mm by taking 50-mm diameter cores. Density samples were collected 72 h before planting and 10 days after the completion of tillage and traffic operations. For each traffic treatment, measurements of ρ_b were taken in triplicate ($n = 3$) from a transect that extended along the field and had three equally-spaced sampling points, and ρ_b determined as per Blake and Hartge [43] (Table 1). Maximum soil bulk density, obtained with the standard Proctor test [44] for the bulked 0–300 mm, was 1.70 g cm^{-3} at a soil water content of 21.20% (w/w). Total porosity of soil $\left(\eta = 1 - \frac{\rho_b}{\rho_P}\right)$ was derived from density properties using a particle density (ρ_P) of 2.65 g cm^{-3}, considered to be appropriate for this soil type [45]. Effective porosity was estimated from soil bulk density ($\eta_e = 0.3 - 0.17\rho_b$) to reflect the interconnected soil pore volume or void space that contributes to soil water flow or permeability [46]. Measurements of soil penetration resistance ($n = 10$) were conducted with a RIMIK®CP-300 penetrometer 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. Gravimetric soil water content (θ_g, % w/w) was simultaneously determined because of its influence on soil strength [47]. Measurements of water content and soil penetration resistance were conducted ten times ($n = 10$) for each traffic treatment. The timing of these two measurements coincided with that of soil bulk density indicated above.

3.3. Soil hydraulic properties

Water infiltration into soil was measured using the double-ring infiltrometer method [48]. Infiltration rates were subsequently obtained by differentiating Kostiakov's equation (Equation (1)) with respect to time to describe the relationship between the rate of infiltration and time (Equation (2)). Measurements were replicated three times ($n = 3$) for each traffic treatment. Infiltration tests were conducted 72 h before planting and 10 days after the completion of tillage and traffic operations.

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

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

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 for the 0–150 mm depth layer was measured for both CTF and non-CTF plots using the constant head test [49]. Intact soil cores were collected from the field at the time density samples were taken (Section 2.2), and transported to the laboratory for determination of K_{SAT}, which was determined within five days of sample collection. The outflow leachate was collected in beakers at the bottom of the column. Measurements of leachate and timing of duration required to obtain the leachate enabled K_{SAT} to be determined. K_{SAT} (mm day^{-1}) for a vertical soil core under constant head is obtained as follows (after [49]):

$$K_{SAT} = \frac{V \times L}{A \times H \times t} \tag{3}$$

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, field capacity) is the highest field-measured water content of a soil after it had been thoroughly wetted and allowed to drain until drainage becomes practically negligible. Laboratory-based procedures to determine field capacity may result in soil water contents that are different from field-measured values of DUL. Crop lower limit (LL, wilting point) is the amount of water remaining after a particular crop has extracted all the water available to it from the soil. Water held between LL and DUL is available to plants (PAWC) and moves only slowly by diffusion. Water held below the lower limit is

Table 1
Soil bulk density (ρ_b), total porosity of soil (η), effective porosity of soil (η_e), drained upper limit (DUL, field capacity), lower limit (LL, wilting point), soil water content at saturation (SAT), and saturated hydraulic conductivity (K_{SAT}) used in APSIM simulations for CTF and non-CTF conditions for a Red Ferrosol in Toowoomba (Queensland, Australia). PAWC is plant available water capacity. The standard deviation (SD) is shown for measured values as ± the mean value ($n = 3$), except when not shown ($n = 1$).

Depth (mm)	ρ_b(g cm^{-3})	η(%, v/v)	η_e(%, v/v)	DUL (m^3 m^{-3})	LL (m^3 m^{-3})	PAWC (m^3 m^{-3})	SAT (m^3 m^{-3})	K_{SAT} (mm day^{-1})
CTF								
0–150	1.22 ± 0.06	54 ± 0.02	9.3	0.300 ± 0.02	0.210	0.090	0.550	1000 ± 6.65
150–300	1.20 ± 0.03	55 ± 0.02	9.6	0.340 ± 0.01	0.240	0.100	0.550	500
300–600	1.20	55	9.6	0.360	0.220	0.140	0.480	100
600–900	1.20	55	9.6	0.350	0.240	0.110	0.440	50
900–1200	1.22	54	9.3	0.360	0.250	0.110	0.430	50
1200–1500	1.25	53	8.8	0.330	0.250	0.080	0.400	25
1500–1800	1.30	51	7.9	0.330	0.270	0.060	0.400	25
non-CTF								
0–150	1.37 ± 0.05	49 ± 0.01	6.7	0.265 ± <0.01	0.220	0.045	0.482	50 ± 0.08
150–300	1.38 ± 0.04	48 ± 0.01	6.5	0.290 ± <0.01	0.250	0.040	0.495	25
300–600	1.30	51	7.9	0.365	0.236	0.129	0.442	10
600–900	1.28	52	8.2	0.354	0.253	0.101	0.410	25
900–1200	1.28	52	8.2	0.364	0.261	0.103	0.407	25
1200–1500	1.27	52	8.4	0.331	0.254	0.077	0.392	25
1500–1800	1.32	50	7.6	0.331	0.274	0.057	0.392	25

unavailable to plants. Saturated water (SAT) content is the maximum amount of water a soil can store, and it is approximately equal to total porosity of soil. The water held between DUL and SAT can drain under the influence of gravity. Although this water is available to plants, often much of it may drain before it can be used [1,50]. The estimation and use of SAT, DUL, LL, and PAWC in APSIM is described in Section 3.6.

3.4. Crop measurements and analyses

The crop was harvested by hand-cutting the entire plants from the entire plot at approximately 20 mm above the soil surface on March 4, 2016. Crop samples were processed to determine grain yield, and the following yield components: harvest Index $\left(HI = \frac{Y}{TB}, \, kg\, kg^{-1}\right)$, the ratio grain yield (Y) to total aboveground biomass (TB) [51], thousand-grain weight (TGW) and number of grains per square meter ([52], Method No.: 73). Grain-N content ([52], Method No.: 48) was used to estimate apparent N recovery in grain by the difference method, referred to here as N use efficiency (NUE). Differences in yield between fertilised and non-fertilised crops, relative to N applied as fertiliser, were used to denote agronomic efficiency (AE). These relationships are shown in Equations (4) and (5), respectively (after [32]):

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

$$AE = \frac{(Y_F - Y_{F=0})}{N_{RATE}} \tag{5}$$

where: NUE is N use efficiency (%) based on apparent N recovery in grain, U_F and $U_{F\,=\,0}$ are N recovered in grain (kg ha^{-1}) 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.

3.5. Fertiliser response, most economic rate of nitrogen and gross margin analysis

Yield-to-nitrogen response relationships were obtained by applying nonlinear regression analyses, and by fitting quadratic functions ($y = a + bx - cx^2$) to the data. The N rate at which the maximum yield (Y_{MAX}) is obtained can be derived by equating the first order differential to zero $\left(\frac{dy}{dx} = b - 2cx' = 0 \therefore x' = \frac{b}{2c}\right)$. The N rate that corresponds with x' is referred to as N_{MAX}. The Most Economic Rate of N (MERN) can be derived from the quadratic response [32,53] by equating the first order differential to the price ratio ($P_R = b - 2cx'$). The price ratio is the ratio between the price of N fertiliser (AUD kg^{-1}) and the price of grain (AUD kg^{-1}) for the year of harvest, which were taken from Incitec Pivot Fertilisers Australia (https://www.incitecpivotfertilisers.com.au/) and Index Mundi (https://www.indexmundi.com/), respectively. Therefore, the optimum N application rate is obtained as follows: $MERN = \frac{b - P_R}{2c}$. This approach has been satisfactorily used in earlier studies [54,55] and is employed here to enable gross margin (GM) analyses to be conducted. Crops' GM were estimated as the difference between gross income (GI) and total variable costs (TVC). Gross margin analyses used the value of MERN to estimate the fertiliser component of the variable costs, and to derive grain yield (Y_{MERN}) from the N response curve at the point where N input matched MERN. Therefore, GM reflects the gross profitability of the crop when the fertiliser N input is optimised.

A simplification of these analyses was to assume that variable costs, other than fertiliser cost, were identical in both traffic systems. In CTF systems commonly used in Australia, the area subject to traffic typically occupies 15% (or less) of the cultivated field area, particularly when permanent zero-tillage (ZT) is practiced. Where CTF is not practiced, and depending upon the configuration of farm vehicles and implements, and number of passes, the cultivated field area affected by traffic is often greater than about 65% when shallow tillage (ST, ≤150 mm deep) is practiced and 45% when ZT is practiced, and it can be as high as 85% in conventional tillage systems that require primary tillage operations prior to crop establishment [56]. Both ZT and ST are widely used in Australia [57], so 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 ST, 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. When ZT was 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 treatment, these relative areas were 15% (trafficked area) and 85% (non-trafficked area). Hence, the corresponding GI for each traffic system was derived by adjusting Y_{MERN} in Equations (6)–(8) by these relative percentages, respectively. This was considered to be a fair approach based on earlier studies [15].

$$GI_{(non-CTF+ST)}:\ Y_{MERN} = \left\{\left(0.35 \times Y_{MERN\ (no-traffic)}\right) + \left(0.65 \times Y_{MERN\ (traffic)}\right)\right\} \tag{6}$$

$$GI_{(non-CTF+ZT)}:\ Y_{MERN} = \left\{\left(0.55 \times Y_{MERN\ (no-traffic)}\right) + \left(0.45 \times Y_{MERN\ (traffic)}\right)\right\} \tag{7}$$

$$GI_{(CTF+ZT)}:\ Y_{MERN} = \left\{\left(0.85 \times Y_{MERN\ (no-traffic)}\right) + \left(0.15 \times Y_{MERN\ (traffic)}\right)\right\} \tag{8}$$

where: Y_{MERN} is the grain yield achieved with a N application rate equivalent to MERN (kg ha^{-1}), 0.65 and 0.35 are the relative areas that were and were not subject to traffic in non-CTF when ST is practiced; 0.45 and 0.55 are the relative areas that were and were not subject to traffic compaction in non-CTF when ZT is practiced; and 0.15 and 0.85 are the relative areas that were and were not subject to traffic compaction in the CTF system, respectively. This assumption was also considered to be appropriate because ZT is practiced by most growers in CTF; except when strategic or occasional tillage is used [58,59].

3.6. Modelling of crop performance

The Agriculture Production System Simulator (APSIM) farming systems framework [33] was used to model crop growth and performance as a means to extrapolate and be able to generalise experimental findings. A process modelling approach was chosen to quantify the long-term impact of soil compaction on crop productivity, as previously described in Antille et al. [60]; except that the SoilWat module in APSIM was used to represent soil water processes instead of SWIM3 [50]. Simulations were conducted to test for RUE, total biomass, and yield of summer-grown (November–March) grain sorghum under CTF and non-CTF conditions on a Red Ferrosol [35]. These simulations were conducted on a continuous basis for 55 years (1960–2015) and simulated results grouped as rainfall categories; namely: driest 30%, wettest 30%, and average 40% years, to investigate the effect of inter-season rainfall variability on crop performance (RUE, total biomass, grain yield) and runoff-rainfall relationships. Climatic data was obtained from the Bureau of Meteorology (Australian Government, http://www.bom.gov.au/) from weather station No.: 41529 (Toowoomba, Queensland) via patched point dataset [61]. For the sake of this study, RUE is defined as the ratio of grain yield (kg ha^{-1}) to total in-crop rainfall [62]. Soil physical and hydraulic properties in CTF and non-CTF, and their use in APSIM, were obtained as explained here.

- Soil bulk density (ρ_b) was measured for the 0–150 mm and 150–300 mm depth intervals and obtained from the APSoil database (https://www.apsim.info/apsim-model/apsoil/) for similar Red Ferrosol to represent the state of the soil without compaction (CTF soil condition) below that depth (300–1800 mm). For non-CTF, it was assumed that ρ_b would increase by approximately 0.1 g cm^{-3} for the 300–600 mm depth interval, as reported in Antille et al. [60] for soil affected by agricultural traffic. Such traffic effect being the result of heavy axle loads, multiple passes or both, noting that traffic-induced stresses in agricultural soils are highest within that depth range (300–600 mm), as shown by Chamen [5]. However, the impact of compaction was assumed to decrease progressively below 600 mm and up to the full depth (1800 mm). This assumption was considered to be fair based on measurements reported by earlier studies that showed a near-linear decrease in soil vertical displacement with an increase in soil depth for vehicles with wheel loads up to 12.5 Mg [39]. Because the soil is naturally denser and is confined at depth, any traffic impact (increase in soil displacement) will be proportionally smaller.

- Drained upper limit (DUL, field capacity) was measured in the field for the 0–300 mm depth interval using the method described in Ratliff et al. [63] and estimated by fitting pedotransfer functions for the 300–1800 mm depth range. Ratliff's method specifies that "*DUL is obtained from analysis of successive measurements of soil water content after the soil had been thoroughly wetted and allowed to drain. Successive measurements of such a thoroughly wetted soil exhibit a monotonic decrease in soil water with time until the drainage rate becomes negligible. The soil would be considered to attain a negligible drainage rate, and to reach DUL, when the water content decrease was about 0.1 to 0.2% water content* per *day*". The pedotransfer functions are specified in a spreadsheet provided as Supplementary data ('PAWCER.xlsx'), which shows the equations used to derive DUL from particle size analysis (PSA) and ρ_b. Particle size analysis was determined with the Pipette method [36].
- Lower limit (LL, wilting point) was estimated by fitting pedotransfer functions for the full 0–1800 mm depth range. Estimations of LL were performed using the 'PAWCER.xlsx' spreadsheet, and the formulae for its calculation also rely on PSA and ρ_b, as described above for DUL.
- Plant available water capacity (PAWC) was calculated for each depth interval by determining the difference between DUL and LL.
- The soil water content at saturation (SAT) was considered to be 97% of total porosity of soil [83].
- Saturated hydraulic conductivity (K_{SAT}) was measured for the 0–150 mm depth interval in both CTF and non-CTF soil conditions, as explained earlier ([49], Equation (3)). Below that depth, representative values of K_{SAT} were taken from Connolly et al. [64] who provided parameter ranges for macropores and micropores for Red Ferrosols after various cropping histories. Values of K_{SAT} for CTF soil (not affected by compaction) included a macropore component. Given that K_{SAT} decreases significantly as a result of field traffic, the contribution from macropores after compaction is reduced. Hence, K_{SAT} values were estimated to reflect the micropore values given by Connolly et al. [64] and the relative change in ρ_b assumed for a given depth. This approach has been employed in the study of Antille et al. [60] to define changes in K_{SAT} as a result of compaction in Grey Vertosols with similar clay contents (albeit different clay mineralogy) to the Red Ferrosol used in our study.

A runoff curve number (CN), that is runoff as a function of total daily rainfall [65], that describes runoff potential for bare-soil, was set at 73 units for CTF, and this was increased by 7 units for non-CTF based on Owens et al. [18]'s study. Default soil evaporation parameters were set according to Kodur [66], which are also available in the APSoil database (https://www.apsim.info/apsim-model/apsoil/). Soil properties and input parameters used in APSIM are shown in Table 1. For modelling purposes in APSIM, grain sorghum was sown every year on a defined sowing rainfall: at least 25 mm over a 7-day period between November and January. If the defined rainfall did not occur, the model was forced to sow a crop on 31[st] January so that cropping could occur all years. The crop was sown at a density of 50,000 plants per ha to match the target plant population of the field experiment, and received a N application rate of 140 kg N ha^{-1}, which corresponded, approximately, with the optimum N application rate (MERN) under CTF in the form of urea (Table 2). Nitrogen was applied 30 days after sowing to be consistent with standard agronomic practice in Queensland [67]. Initial soil water content in the first year of the simulations was set at $0.95 \times PAWC$ and this value was determined by prior running the model for 10 years. The APSIM-Sorghum module within APSIM has been well-tested across soil and climate conditions both in Australia and internationally for a range of farming systems [68]. However, to further represent the conditions of the current experimental site, the model was calibrated for both CTF and non-CTF systems, and validated against measured yield data from the site (Table 1). The 55-year average modelled yield data was about 10% higher than field-measured yield data, but this difference was considered to be acceptable given the modelled data were within the range of reported yields in the region [69].

3.7. Statistical analyses

Statistical analyses were undertaken with GenStat Release® 19[th] Edition [70] and involved analysis of variance (ANOVA). The ANOVA model used in GenStat® was $\frac{\textit{Traffic system} \times \textit{Control vs. Treatment}}{(\textit{Fertiliser type} \times \textit{Fertiliser rate})}$; where: 'Traffic system' refers to CTF and non-CTF, 'Control' and 'Treatment' are non-fertilised ($N = 0$) and fertilised ($N \neq 0$) plots, respectively, 'Fertiliser type' refers to N source (UAN, ENTECT®, urea), and 'Fertiliser rate' is N application rate (0, 100, 200, 300 kg ha^{-1} N). Subsequently, the least significant differences (LSD) were used to compare means with a probability level of 5%. Statistical analyses were graphically assessed by means of residual plots and normalisation of data was not required. Yield-to-N responses were investigated by means of nonlinear (quadratic) regression analyses. Nonlinear regression analyses were also used to describe the relationship between NUE and fertiliser N applied from which NUE and AE corresponding to MERN were derived. Analytical values are reported as the mean ± standard deviation (SD), except when $n = 1$. Statistical outputs for grain yield and yield components (total aboveground biomass, harvest Index, grain-N content and N recovery in grain, thousand-grain weight and number of grains per square meter) are reported as Supplementary data in Tables 1S–7S Statistical outputs (two-way ANOVA: traffic system, fertiliser type) for MERN, Y_{MERN}, N_{MAX} and Y_{MAX} are presented as Supplementary data in Table 8S. A two-way ANOVA testing the effect of the traffic treatment and soil depth was conducted for soil penetration resistance and soil water content data ($n = 10$).

4. Results

4.1. Soil physical and hydraulic properties

Soil penetration resistance and soil water content for traffic treatments representing CTF and non-CTF systems are shown in Fig. 2. Differences in (gravimetric) soil water content between the two traffic treatments were not significant ($P > 0.05$); therefore, there was no need to adjust cone Index by soil water [47]. Overall, there were significant differences ($P < 0.05$) in penetration resistance between CTF and non-CTF, which were observed throughout the profile; except in the 0–50 mm depth interval. Mean values of cone Index in the 0–500 mm depth range were 2.51 and 5.15 MPa (LSD 5% level: 1.085) for CTF and non-CTF, respectively. In both traffic treatments, soil penetration resistance increased with an increase in soil depth, but to a greater extent in wheeled (non-CTF) than to non-wheeled (CTF) soil. Differences in penetration resistance found between the two traffic treatments were consistent with measurements of soil bulk density (Table 1).

Measurements of water infiltration rates for CTF and non-CTF re-

Table 2
The Most Economic Rate of Nitrogen (MERN) application for grain sorghum, grown on a Red Ferrosol in Toowoomba (Queensland, Australia), as derived from the yield-to-nitrogen response curves for both CTF and non-CTF, respectively. (†) P_G: price of grain, P_N: price of nitrogen, R_P: price ratio (P_N/P_G), N_{MAX}: N application rate required for maximum yield (Y_{MAX}), and crop yield for N = MERN (Y_{MERN}), $n = 3$. UAN is urea ammonium nitrate (32% N, solution), ENTEC® is urea treated with 3,4-dimethyl pyrazole phosphate (DMPP, 46% N), and urea (46% N). Mean values are shown ± standard deviation (SD). Currency conversion: AUD1 ≈ USD0.75. A summary of the statistical output for MERN, Y_{MERN}, N_{MAX} and Y_{MAX} is presented as Supplementary data in Table 8S.

Traffic treatment	Source	P_G	P_N	R_P	Response	P-value	R^2	MERN	Y_{MERN}	N_{MAX}	Y_{MAX}
Unit	–	AUD kg^{-1}			–	–	–	kg ha^{-1}			
non-CTF	UAN	0.23	0.77	3.3	$y = 1029 + 13.5x - 0.04x^2$	0.07	0.64	117 ± 23.3	2012 ± 46.5	156 ± 13.6	2077 ± 30.8
	ENTEC®	0.23	0.96	4.2	$y = 1062 + 7.6x - 0.02x^2$	0.16	0.58	73 ± 23.6	1491 ± 97.3	163 ± 29.7	1678 ± 20.9
	Urea	0.23	0.75	3.3	$y = 1067 + 11.4x - 0.04x^2$	0.13	0.72	111 ± 33.9	1884 ± 53.3	155 ± 18.4	1957 ± 28.6
CTF	UAN	0.23	0.77	3.3	$y = 1527 + 27.9x - 0.08x^2$	0.09	0.53	152 ± 6.0	3902 ± 37.2	173 ± 3.8	3997 ± 33.7
	ENTEC®	0.23	0.96	4.2	$y = 1575 + 16.1x - 0.04x^2$	0.03	0.51	140 ± 14.9	2998 ± 57.7	190 ± 5.1	3101 ± 41.5
	Urea	0.23	0.75	3.3	$y = 1488 + 23.5x - 0.07x^2$	0.20	0.43	142 ± 7.8	3385 ± 33.5	165 ± 5.2	3423 ± 29.2

(†) The price of grain and price of nitrogen were sourced from Index Mundi (https://www.indexmundi.com/) and Incitec Pivot Fertilisers Australia (https://www.incitecpivotfertilisers.com.au/), respectively.

ported the relationships shown in Equations (9) and (10), respectively. The graphical information that describes these relationships is presented as Supplementary data (Fig. 1S).

$$\text{CTF}: I_r = 50.29t^{-0.816}, \quad (R^2 = 0.57, \ n = 3) \tag{9}$$

and

$$\text{non}-\text{CTF}: \quad I_r = 4.88t^{-0.435}, \quad (\mathrm{R}^2 = 0.72, \ n = 3) \tag{10}$$

Infiltration rates were significantly lower in non-CTF compared with CTF at any given time (P-values <0.05). Infiltration rates for CTF soil appeared to stabilise at $0.35 \le t(h) \le 1$, but subsequently dropped and stabilised again at $t(h) > 1$. This abrupt change in infiltration rates appears to reflect changes in soil hydraulic properties between topsoil and subsoil, which may be due to the tillage operation conducted when the experimental site was established. These results are consistent with measurements of K_{SAT} reported in Table 1, which were about 20 times higher ($P < 0.05$) in CTF compared with non-CTF; thus, indicating a significant impact of compaction on soil pores connectivity. This effect was also shown by differences in effective porosity of soil (η_e) between the two traffic treatments.

4.2. Grain yield and yield components

There were significant differences in grain yield between the two traffic treatments as well as between fertilised and non-fertilised (controls) crops, which were observed in CTF and non-CTF (P-values <0.05). Comparisons between controls showed that grain yield was about 480 kg ha^{-1} higher in CTF compared with non-CTF ($P < 0.05$). Overall, grain yield of fertilised crop under CTF was approximately 1400 kg ha^{-1} higher compared with fertilised crop in non-CTF ($P < 0.05$). On average across fertiliser treatments, the optimum N application rates (MERN), and corresponding grain yields, were 144 kg ha^{-1} N and 3428 kg ha^{-1} for CTF, and 100 kg ha^{-1} N and 1796 kg ha^{-1} for non-CTF. The fertiliser type effect on grain yield was not significant, which was consistent at any given rate of N, and no fertiliser type × N application rate effect on grain yield was recorded in either traffic treatment (P-values >0.05) (Fig. 3A–B). We hypothesise that smaller increments in N application rates than those used in this study could have potentially picked differences in fertiliser type effects. However, the compaction effect appears to be greater than that of fertiliser type. Therefore, fertiliser type effects could be still masked at N increments smaller than those used in this study. Future experimental work may like to address this uncertainty and derive the fertiliser response by using smaller increments in N application rates.

There were significant differences in aboveground biomass between CTF and non-CTF, and between fertilised and non-fertilised crops, which were observed in both traffic treatments (P-values <0.05). Overall, total aboveground biomass was 35% higher in CTF compared with non-CTF (Fig. 4A–B); mean values for CTF and non-CTF were 7.9 Mg and 5.8 Mg per ha, respectively. There was also a N rate effect on aboveground biomass (P = 0.024), but the overall fertiliser type effect was not significant (P > 0.05). Overall differences in harvest Index (HI, Fig. 4C–D) between CTF and non-CTF were significant as well as between fertilised ($N \neq 0$) and non-fertilised ($N = 0$) crops in both traffic treatments (P-values <0.05). Thousand grain weight (TGW) and number of grains per m^2 (Fig. 2SA-2SD) both showed significant differences between traffic treatments (P-values <0.05), and therefore consistent with grain yield results. There was no fertiliser type effect on TGW or grain count (P-values >0.05). However, there was a N rate effect on number of grains per m,[2] which was recorded in both traffic treatments (P = 0.007). Overall, across all fertiliser types and N application rates (including controls), mean TGW (±SD) and mean number of grains per m^2 (±SD) were 22.2 ± 0.58 g and 11854 ± 3711 for CTF, and 20.3 ± 1.23 g and 6605 ± 1682 for non-CTF, respectively. Number of grains per m^2 in non-fertilised crop was about half that of fertilised crop ($P < 0.05$).

4.3. Nitrogen recovery and fertiliser nitrogen use efficiency

Total grain-N (TG_N) was significantly higher in CTF compared with non-CTF (Fig. 3SA-3SB, P = 0.022), but overall differences between the two traffic treatments were small (2.10 ± 0.04% *vs.* 2.00 ± 0.17%, respectively). Nitrogen recoveries in grain are shown in Fig. 5A and B. There were no fertiliser type or N rate effects on TG_N, which was observed in both traffic treatments (P-values >0.05). Differences in TG_N between fertilised and non-fertilised crops were significant in both traffic treatments, with lower values in non-fertilised crops (P = 0.021).

Results showed that NUE, expressed as apparent N recovery in grain, was significantly higher in CTF compared with non-CTF ($P < 0.001$), as shown in Fig. 6. Differences in NUE between-traffic treatments were observed at any given rate of N. Fig. 6 allows for a quick comparison of NUE between CTF and non-CTF if N inputs were to be optimised in both traffic systems. The MERN values reported in Table 2, averaged across fertiliser products, can be substituted by 'x' to solve the equations that appear in Fig. 6. The solution of these equations for x = MERN returns the traffic systems' 'average' NUE when N inputs are optimised. This simple comparison shows that NUE is expected to be approximately 45% higher in CTF compared with non-CTF, which would have significant financial (increased economic return from applied fertiliser-N) and environmental (reduced N loss) implications. Agronomic efficiencies (AE) were

[2] The yield of an adapted crop variety when grown under rainfed conditions with best management practices to minimise growth limitations from nutrients, pests and diseases (Yield Gap Australia, http://yieldgapaustralia.com.au/).

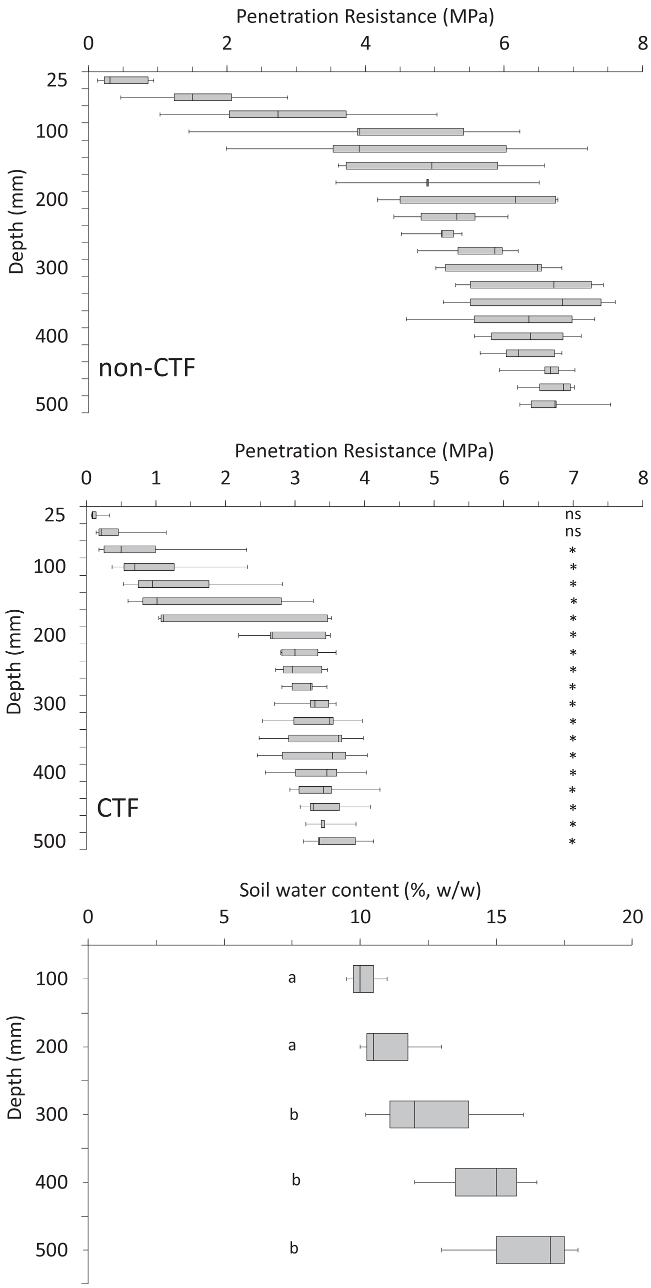

Fig. 2. Soil penetration resistance ($n = 10$) and gravimetric soil water content ($n = 20$) observed at the experimental sites for the two traffic treatments representing controlled (CTF) and non-controlled traffic farming (non-CTF) systems, respectively. In both datasets, each box-plot shows Min, Q_1, Med, Q_3, and Max, respectively. Penetration resistance: $P < 0.001$ (traffic treatments, LSD 5% level: 0.243), $P < 0.001$ (depth, LSD 5% level: 0.767), $P = 0.015$ (traffic treatment × depth, LSD 5% level: 1.085). Comparisons between-traffic treatments: ns – not significant, * significant. Soil water content: $P > 0.05$ (traffic treatments), $P = 0.049$ (depth, LSD 5% level: 4.01). Comparisons-between depths: different letters indicate that mean values of soil water content (%, w/w) are significantly different.

significantly higher in CTF compared with non-CTF, as shown in Fig. 7. There was no fertiliser type effect on AE, but this decreased in a nonlinear fashion with an increase in N application rate. Mean AE across all fertiliser types and N application rates were 10 ± 7.3 kg kg^{-1} for CTF and 4 ± 3.5 kg kg^{-1} for non-CTF. As shown above for NUE, if N application was to be optimised (applied at MERN) in both traffic systems, AE would be 13 kg kg^{-1} for CTF and 8 kg kg^{-1} for non-CTF.

4.4. Fertiliser response, most economic rate of nitrogen and gross margin analysis

Table 2 shows the most economic rate of N (MERN) and corresponding yield (Y_{MERN}) as derived from the yield-to-N response relationships, and price ratios (P_R) for the year of harvest. For most treatments, the regression analyses showed that yield-to-N responses were fairly well described ($R^2 > 0.50$; except urea in CTF: $R^2 = 0.43$) by quadratic models when these models were fitted to the data. Quadratic functions provide a satisfactory biological description of the yield-to-N response, and therefore may be used despite of non-statistical significance of the quadratic term [71]. Therefore, the use of such nonlinear models may be justified as most responses produced acceptable fits [72]. Yield penalties may occur at high N application rates when crop demand for water cannot be met by soil water availability or rainfall [23,32]. Based on the data presented in Table 2, Y_{MERN} values averaged across fertiliser types would be 3500 kg ha^{-1} for CTF and 1800 kg ha^{-1} for non-CTF attained with N inputs (i.e., average MERN) equivalent to 144 kg ha^{-1} and 100 kg ha^{-1}, respectively.

For both traffic treatments, the variable cost of AUD169 ha^{-1} used for gross margin (GM) analyses included the costs of seed, field operations (including equipment maintenance), and agrochemicals used for crop protection. Average GM calculations across all fertiliser types were approximately 20% higher in CTF (ZT) compared with non-CTF under ZT and about 50% higher for non-CTF under ST. Differences in GM between-fertiliser treatments are due to differences in the cost of unit N, particularly for ENTEC® (Table 3). Thus, the impact of N fertiliser cost on GM was more significant in non-CTF; this being the combined effect of lower yield and lower NUE achieved in this traffic system.

4.5. Modelling of crop performance, rainfall use efficiency and rainfall-runoff relationships

APSIM-modelled grain yield, total biomass, RUE and runoff for CTF and non-CTF conditions as a function of long-term (1960–2015) rainfall data for Toowoomba (Australia) are shown in Fig. 8A–D. Mean values for traffic treatments were consolidated in Table 4. Simulations suggested that widespread soil compaction in non-CTF can reduce grain yield by up to 42%, total biomass by 44%, and RUE by 33%, concurrently with an increase in all-years average runoff from about 11% to about 27% (expressed as % of in-crop rainfall). Given the size of these differences, the effects are considered to be significant across all rainfall conditions. However, the impact of compaction on grain yield is relatively greater in below-average rainfall years (30th percentile, in-crop rainfall: ≤330 mm) compared with average (in-crop rainfall: 330–450 mm) or above-average (70th percentile, ≥450 mm in-crop rainfall) rainfall conditions when yield is less limited by water availability. Simulated results also suggested non-CTF to suffer from significantly greater inter-season variability in crop yields (by a factor of about three), as shown in Table 4 by the calculated SD values of each rainfall category.

Available soil water, both at sowing and throughout the cropping season, would tend to increase with an increase in rainfall, but to greater extent in CTF compared with non-CTF because of the effect of compaction on water infiltration into soil. In above-average rainfall years, simulated results showed that the amount of runoff generated from non-CTF soil can be double that of CTF (Table 4). In below-average rainfall years, the opportunities for crop establishment, particularly early sowing, will be likely restricted by soil water availability at the start of the season, and this can compromise yield potential [73]. Simulations showed that the initial soil water contents, obtained by a 10-year prior run of the model, were 629 mm and 616 mm for CTF and non-CTF, respectively (115-year average). But differences in soil water at sowing between the two traffic treatments were up to 46 mm (‘dry’ years' average). Differences in soil water availability at sowing reflect the impact of traffic on water holding capacity during the fallow period, and possible effects on sowing opportunity and timeliness.

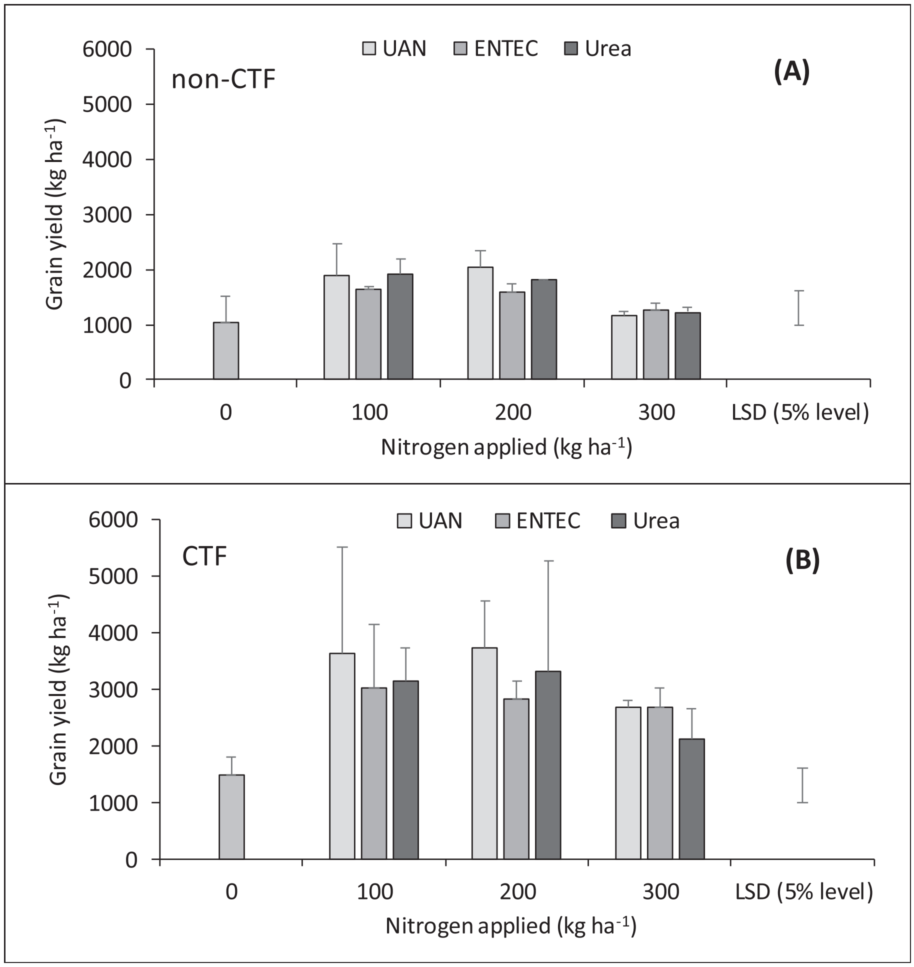

Fig. 3. Fertiliser effect on grain yield for two traffic treatments representing non-controlled (non-CTF) and controlled traffic farming (CTF) systems, respectively. Error bars on mean values denote the standard deviation ($n = 3$). The LSD (5% level) error bar is shown for “Traffic × Control *vs.* Treatment/(Fertiliser × Rate)”. The ANOVA table, and LSD values for other levels of interaction, are reported as Supplementary data in Table 1S.

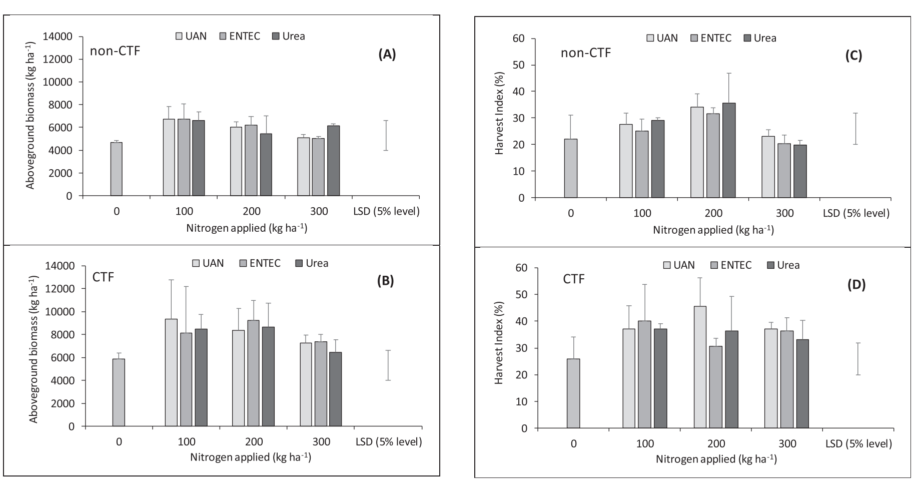

Fig. 4. Fertiliser effect on total aboveground biomass (A and B) and harvest Index (C and D) for two traffic treatments representing non-controlled (non-CTF) and controlled traffic farming (CTF) systems, respectively. Error bars on mean values denote the standard deviation ($n = 3$). The LSD (5% level) error bar is shown for “Traffic × Control *vs.* Treatment/(Fertiliser × Rate)”. The ANOVA tables, and LSD values for other levels of interaction, are reported as Supplementary data in Tables 2S and 3S for total aboveground biomass and harvest Index, respectively.

5. Discussion

5.1. Effect of soil compaction on soil, soil hydraulic properties, and water economy

Random field traffic leads to widespread compaction and soil structural degradation, thus affecting important soil processes and function, and consequently crop productivity [74], as shown also by our study. Compacted soil, representing the non-CTF traffic system, exhibited higher bulk density (and therefore lower total and effective porosity) and cone Index (0–500 mm) than the CTF system, represented by untrafficked soil (Fig. 2). Soil cone Index within this study was consistent with soil bulk density data. Measurements of penetration resistance were conducted at soil water contents between 10% and 18% (w/w) depending on

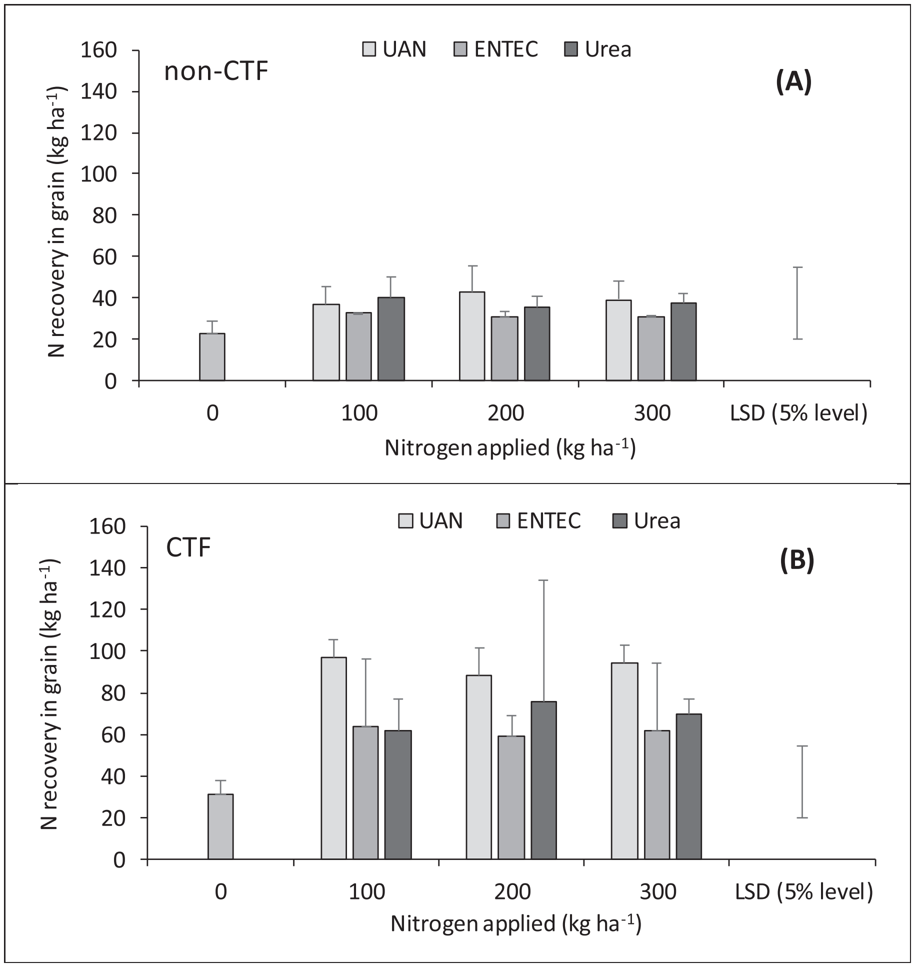

Fig. 5. Fertiliser effect on nitrogen (N) recovery in grain for two traffic treatments representing non-controlled (non-CTF) and controlled traffic farming (CTF) systems, respectively. Error bars on mean values denote the standard deviation ($n = 3$). The LSD (5% level) error bar is shown for "Traffic × Control *vs.* Treatment/(Fertiliser × Rate)". The ANOVA table, and LSD values for other levels of interaction, are reported as Supplementary data in Table 4S.

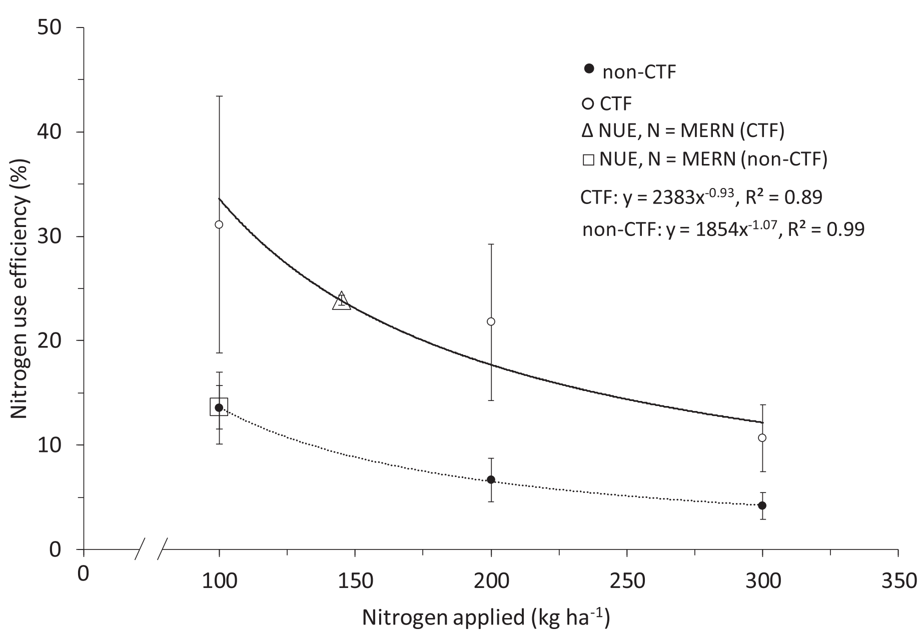

Fig. 6. Relationship between N use efficiency (NUE) and N application rate recorded for two traffic treatments representing controlled (CTF) and non-controlled traffic farming (non-CTF) systems, respectively. Symbols (Δ) and (□) represent NUE of the CTF and non-CTF treatments, respectively, at N application rates equivalent to MERN averaged across all fertiliser types. Error bars denote SD of the mean, $P < 0.05$, $n = 9$, except for N = MERN ($n = 3$).

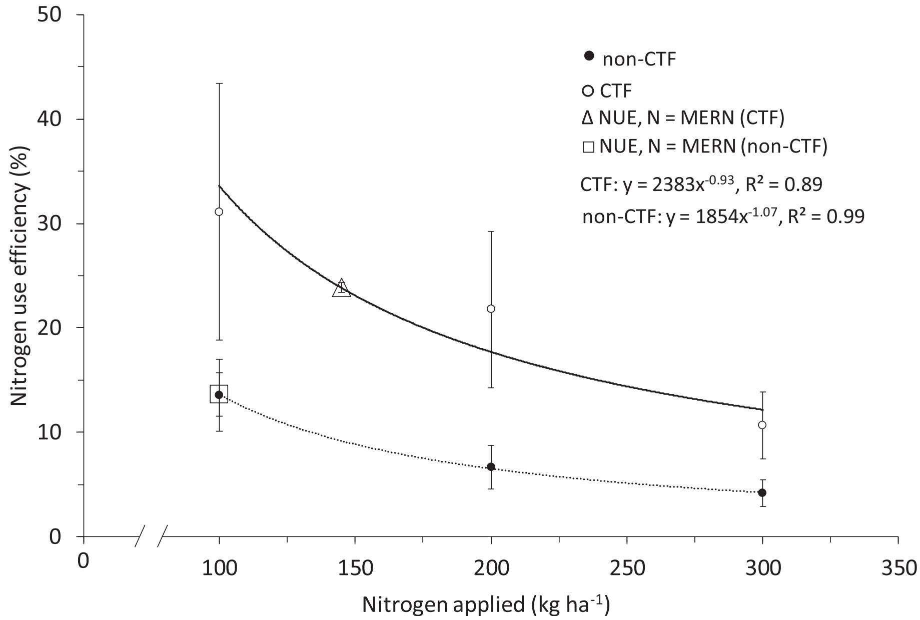

Fig. 7. Relationship between agronomic efficiency (AE) and N application rate recorded for two traffic treatments representing controlled (CTF) and non-controlled traffic farming (non-CTF) systems, respectively. Symbols (Δ) and (□) represent AE of the CTF and non-CTF treatments, respectively, at N application rates equivalent to MERN averaged across all fertiliser types. Error bars denote SD of the mean, $P < 0.05$ and $n = 9$, except for N = MERN ($n = 3$).

Table 3
Gross income (GI), total variable cost (TVC), and gross margin (GM) estimated for grain sorghum, grown on a Red Ferrosol in Toowoomba (Queensland, Australia), based on N application rates equivalent to MERN and the corresponding Y_{MERN}, presented in Table 2. Constant costs were estimated at AUD169 ha^{-1} in both traffic treatments and included cost of seed, field operations and crop protection. ZT: zero-tillage, ST: shallow tillage. The number in brackets denotes wheeled areas in the ZT and ST systems expressed as percent of cultivated field area. Note that CTF is assumed to be in ZT, which is standard practice in Australia [97]. Currency conversion AUD1 ≈ USD0.75.

Traffic and fertilizer treatment		GI (AUD ha^{-1})		Fertilizer cost	TVC	GM (AUD ha^{-1})	
		ZT (45%)	ST (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	–

soil depth, which were below the soil water content (21.20%, w/w) required, as per Standard Proctor test, for maximum dry bulk density (1.70 g cm^{-3}). The Proctor test suggested that soil's susceptibility to compaction at the time of traffic was below its maximum susceptibility and explains the fact that repeated passes of a relatively light-weight tractor [41] were needed to attain the desired soil bulk density in the non-CTF treatment. The Proctor density was within the range reported in other studies for Ferrosols [75].

Infiltration characteristics of CTF soil were significantly better than non-CTF. Steady-state infiltration rates were significantly higher in CTF compared with non-CTF (Equations (9) and (10), respectively, Fig. 1S), consistent with differences in saturated hydraulic conductivity between the two traffic systems (Table 1). Chyba et al. [76] reported steady-state infiltration rates up to 6 times higher in non-trafficked compared with trafficked soil and showed a non-linear decrease in steady-state infiltration rates with increased number of tractor passes (from 0 to 3 passes using a Massey Ferguson 8480). Modelled data derived from APSIM simulations were consistent with field measurements of water infiltration and help explain differences in yield and yield components, RUE and fertiliser NUE between the two traffic treatments.

Fig. 8 showed that in both traffic systems, the amount of runoff increases with rainfall, but to greater extent in non-CTF compared with CTF. Predicted runoff in average (in-crop) rainfall years was about 35 mm, which compares with little more than 100 mm in non-CTF. Expected differences in runoff between CTF and non-CTF in a winter crop in SE Queensland, such as in the study of Hussein et al. [19], may be inferred from Fig. 8D by examining the simulated rainfall-runoff relationship in 'dry' years. Given the conditions set for our analyses, in-crop rainfall inputs of 300 mm (or less) may result in about 20 mm (or less) runoff in CTF, which compares to about 60 mm (or less) in non-CTF. But differences in runoff between the two traffic systems are greater than about 100 mm in 'wet' years (in-crop rainfall ≥450 mm). This suggests that there may be less opportunity for CTF to reduce runoff in winter-grown crops such as wheat. Results derived from runoff-rainfall simulations agree with findings from earlier studies [3] further demonstrating the impact of compaction on soil water retention and the implications for increased runoff risk. For example, functional relationships between water infiltration into soil and tractor wheeling developed by Li et al. [77] showed an asymptotic increase in CN as wheeling energy applied to soil increased (see Fig. 2 in Ref. [77]). Similar relationships were also shown by Godwin and Dresser [78] for northern European conditions, which reflect adverse effects of field traffic on soil hydraulic properties and soil water retention [79].

Reduced hydraulic conductivity when soil undergoes compaction occurs because of reduced pore size and size distribution, and disrupted pores' connectivity [80]. Reported reductions in soil pore volume due to

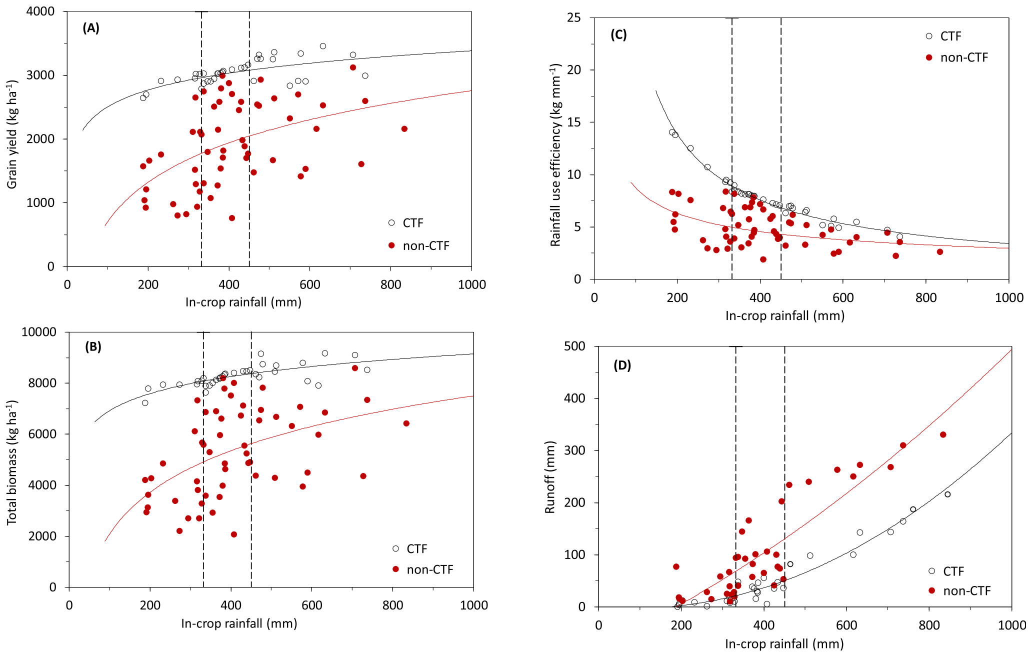

Fig. 8. Long-term (1960–2015) simulation of grain yield (A), total biomass (B), rainfall use efficiency (C) and runoff (D) as a function of in-crop rainfall. Modelled data for grain sorghum-fallow cropping on a Red Ferrosol in Toowoomba (Queensland, Australia) for controlled (CTF) and non-controlled traffic farming (non-CTF) systems, respectively. Continuous lines show the best fit to predicted data. Dotted vertical lines show the 30th (left) and 70th (right) percentiles rainfall, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

agricultural traffic are often between 10% and 70% in the top 500 mm of the profile, depending on traffic intensity, but such reductions can also occur with relatively light (e.g., 5 Mg wheel load) farm equipment [81]. Decreased pore space and disruption of pores' connectivity means that there is less volume available for water storage and that soil water is retained more tightly through capillary attraction [82]. For the 0–300 mm depth interval, our results (Table 1) suggested that a little less than 15% increase in soil bulk density, due to compaction, can reduce PAWC by about 50%. Therefore, field capacity may be restored quicker in non-CTF soils, but limited PAWC will impact crop performance (increased frequency and intensity of water stress), more so in rainfall-limited environments [83]. Impaired internal drainage due to compaction increases the risk of waterlogging [84], which in turn can increase the risk of N loss through denitrification [7,85].

Modelled RUE (Fig. 8C) showed relatively high sensitivity to changes in soil compaction, but more so in average and below-average rainfall years. The analysis showed that RUE may be increased from 6.3 to 13.8 kg mm^{-1} in dry years (≈200 mm in-crop), from 4.6 to 7.5 kg mm^{-1} in average years (≈400 mm in-crop), and from 3.8 to 5.3 kg mm^{-1} in wet years (≈600 mm in-crop) if the system was managed under CTF. This will also lead to concurrent reductions in runoff, and likely sediment, pesticides and nutrient transport in overland flow both on- and off-farm, and increased grain production [18,59]. The seasonal rainfall pattern of southern Queensland means that approximately 60%–70% of total annual rainfall occurs between October and March. Therefore, changes in soil conditions, such as in CTF, that mitigate soil/water and environmental losses of nutrients will have a significant impact on yield reliability of summer-grown crops [68]. This is an important consideration for rainfed cropping systems where water is often the main factor influencing crop yield [86]. APSIM simulations of RUE for 'dry', 'average' and 'wet' seasons may be used to estimate water-limited yield[2] to subsequently inform fertiliser decisions if historical yield-to-N response or yield map data are available [54,87]. For the northern grain sorghum-growing region of Australia, Yield Gap Australia (http://yieldgapaustralia.com.au/) shows a 15-year (2000–2014) actual yield[3] average of 2900 kg ha^{-1}, albeit derived from naturally more productive soils such as Vertosols (data not available for Red Ferrosols). Despite this, APSIM simulations suggested that actual yields recorded at regional level could be exceeded in most years if the crop was managed under CTF, but not under a random, non-controlled, traffic system. Another significant impact of increased RUE is on the opportunities for successful crops using double- and inter-cropping. In the region where this study was conducted, the cropping frequency can be increased from typically less than 0.7 in non-CTF systems with conventional tillage to about 1.2 crops a year when CTF is coupled with no-tillage [9,88]; particularly, if sorghum can be sprayed-off at physiological grain maturity so as to maximise water conservation for the winter-sown crop [89].

5.2. *Effect of soil compaction on grain yield, yield components, and fertiliser nitrogen use efficiency*

Grain yield of sorghum is set at flowering; the time from mid-flowering onwards being critical for determination of number and weight of grains [90], and these two yield components are affected by the size of the canopy. Therefore, any environmental (e.g., water, temperature, radiation) and nutritional stress will impact on grain yield [91]. The flowering phase is short (4–8 days) and the crop is rather sensitive to water deficits. When water stress is not a limiting factor, yield potential is positively correlated with number of grains per square meter that results from increased number of grains per panicle [92]. Grains' weight depends on the rate of dry matter accumulation in grain and the duration of the grain-filling phase, and although important, it contributes less to yield formation than number of grains. Yield potential is positively correlated with aboveground biomass; thus, higher grain yields can be achieved when the crop accumulates greater biomass at mid-flowering [73].

Grain yield in controls plots (zero-N) reflected differences in PAWC and soil N supply throughout the cycle in both traffic treatments. Total aboveground biomass at harvest (Fig. 4A–B, Table 2S), number of grains per square meter and TGW (Fig. 2SA-2SD, Tables 6S–7S) found within this work all showed significant differences between the two traffic treatments, which explains overall differences in grain yield observed between CTF and non-CTF (Fig. 3A–B, Table 1S). The adverse effects on yield and yield components observed in non-CTF reflect the crop's

[3] Average yields achieved in commercial fields. Reflects seasonal conditions as well as farmers' natural endowment, access to technology, and their skill and exposure to market forces (Yield Gap Australia, http://yieldgapaustralia.com.au/).

Table 4
Long-term simulations of grain yield, rainfall use efficiency (RUE), and total biomass for a grain sorghum-fallow cropping system on a Red Ferrosol in Toowoomba (Queensland, Australia) under CTF and non-CTF conditions, respectively. Simulated results are grouped into three rainfall categories, namely: above-average (70th percentile, ≥450 mm in-crop rainfall), average (330–450 mm in-crop rainfall), and below-average (30th percentile, ≤330 mm in-crop rainfall), respectively. "Δ" is predicted difference between CTF and non-CTF. Values are presented as mean ± standard deviation (SD).

Rainfall category	Yield (kg ha^{-1})			Total biomass (kg ha^{-1})			RUE (kg mm^{-1})			Runoff (% of in-crop rainfall)	
Traffic system	CTF	non-CTF	ΔY	CTF	non-CTF	ΔTB	CTF	non-CTF	ΔRUE	CTF	non-CTF
Below-average	2868 ± 144	1446 ± 546	1422	7897 ± 301	4107 ± 1305	3790	10.9 ± 2.22	5.5 ± 1.95	5.4	3.1 ± 1.88	12.8 ± 10.38
Average	3022 ± 89	2042 ± 635	1020	8196 ± 260	5591 ± 1724	2605	7.9 ± 0.54	5.2 ± 1.69	2.7	9.1 ± 3.68	23.9 ± 11.57
Above-average	3160 ± 216	2243 ± 549	918	8597 ± 418	6121 ± 1420	2476	5.8 ± 0.96	3.9 ± 1.19	1.9	20.0 ± 2.56	43.3 ± 4.26
Mean ± SD	3030 ± 149	1910 ± 414	1120 ± 266	8230 ± 351	5273 ± 1044	2957 ± 724	8.2 ± 2.59	4.9 ± 0.84	3.3 ± 1.90	10.7 ± 8.57	26.7 ± 15.44

sensitivity to changes in the soil physical environment as a result of compaction, which led to impaired N and water uptake, and therefore lower use efficiency [93]. Similar observations were made by Ningping and Edwards [94] attributing reduced water and nutrient uptake to increased soil strength, and consequently, impaired root growth, function and distribution in soil [95]. Our study showed that N source (fertiliser formulation) did not appear to have any clear effect on yield or yield components, particularly for the crop grown in non-CTF soil. This confirmed that compaction was the main factor influencing yield and yield-to-N response, and that N recovery by the plant can be significantly affected in structurally degraded soils, as shown by Gregorich et al. [28] and Garcia et al. [96]. Increased N application rate in non-CTF soil showed little or no effect on yield and yield components, and N recovery in grain, and these effects were observed regardless of fertiliser formulation. Additional N fertilisation, as shown by Gregorich et al. [97], or changes in N fertiliser source did not appear to compensate for lower crop agronomic performance caused by compaction.

Zhao et al. [98] showed N deficiency prior to mid-flowering (about 60 days after emergence) to be well correlated with leaf area, aboveground biomass and photosynthetic rate; this latter effect also shown by Lamptey et al. [99]. Muchow [100] also showed reduced N uptake when plant growth was restricted by soil water availability. Therefore, the rate of N uptake prior to mid-flowering in non-CTF is likely to have been suboptimal, regardless of N application rate. At later stages of development, the rate of N uptake declines as the plant starts remobilising N stored in plant biomass [101]. Co-limitation of water and N uptake in the non-CTF treatment reduced the size of the canopy, N accumulation in aboveground biomass and its subsequent translocation to grains thereby compromising grain yield [102]. These observations were confirmed by differences in harvest Indices and N recoveries in grain recorded for the two traffic treatments (Fig. 4C–D and 5A-5B). Hammer and Broad [103] further explained variations in harvest Indices by differences in assimilation during grain-filling and remobilisation of assimilates prior to anthesis. Both NUE, expressed as apparent N recovery in grain, and AE were significantly lower in non-CTF compared with CTF at any given N application rate (Figs. 6 and 7). If N was to be applied at a rate equivalent to the average MERN of each system,[4] NUE and AE would be 23.9% and 11.4 kg kg^{-1} for CTF and 13.6% and 9.6 kg kg^{-1} for non-CTF, respectively. Thus, avoidance of traffic compaction and management of the crop and soil under a CTF system can potentially lead to significant improvements in both metrics compared to non-CTF. As demonstrated by these experiments, this may be possible because of significantly higher yields achieved with CTF, and despite of increased MERN relative to non-CTF.

Increasing grain yield without compromising N content in grain requires a concurrent increase in crop-N accumulation [104]. The crop grown under CTF showed relatively higher grain-N contents, and therefore grain-N recovery, compared with non-CTF, but overall treatment differences were small. Differences in N recoveries between the two traffic treatments were mainly explained by differences in grain yield (Fig. 5A–B). This also reflects the difficulty in simultaneously increasing grain N recovery and grain yield [105], more so in CTF than non-CTF. However, early work in Queensland [106] showed that this may be managed by applying foliar N (solution) at flowering to increase grain-N content, and potentially yield, provided soil water or rainfall were not limiting at terminal stages of crop development.

The companion study by Hussein et al. [19] on winter wheat questioned how the response of a (dryland) summer crop such as sorghum would be to the combined effects of compaction, N source and N rate. In SE Queensland, wheat and sorghum are grown under different rainfall regimes; winter-grown crops have greater reliance on stored soil water whereas summer-grown crops rely on in-crop rainfall. While a direct

[4] From Table 2, average MERN values across all fertiliser types were 100 and 144 kg N ha^{-1} for non-CTF and CTF, respectively.

comparison between the two crops may be difficult because of their physiological responses to management × environment, it is possible to state that co-limitation of water and N was a key factor affecting yield, and this effect was exacerbated by compaction. Rainfall conditions from January onwards, and for the rest of the 2015–2016 growing season, were drier than the same period of an 'average' season (Fig. 1). Such conditions in summer emulated those of the typically drier winter period in SE Queensland and indicated that compaction can have similar detrimental effects on soil water availability and N acquisition in both crops. Sorghum is a more resilient crop and it can withstand environmental stresses (e.g., lack of soil water availability) to greater extent than wheat. However, our work showed that traffic compaction can magnify the impact of such stresses by inducing a knock-on effect on N uptake. There is a need to explore the longer-term effects of compaction and N fertilisation on wheat, and this may be possible by applying the modelling approach developed for sorghum as part of the current study.

5.3. Modelling of crop performance

The 55-year (1960–2015) grain yield simulations of sorghum grown on a Red Ferrosol in Toowoomba showed that, for an average in-crop rainfall of ≈410 mm, an average yield of ≈3040 kg ha^{-1} can be achieved in CTF, but this could reduce by about 30% if the crop was grown under non-CTF. This compares with a 2-year average yield reduction of about 20% found by Ishaq et al. [107] [5] for sorghum grown on compacted soil. Measured yields for CTF and non-CTF in our study were 3020 and 1620 kg ha^{-1} (averaged across all fertiliser types and N application rates). Thus, the model appears to underestimate yield a little in the non-CTF condition, considering that total in-crop rainfall for the 2015–2016 season was about 390 mm, that is, marginally drier than an 'average' season. Simulations also showed smaller yield penalties in higher-yielding seasons (≥450 mm in-crop rainfall) when water was not limiting. For lower-yielding seasons (≤330 mm in-crop rainfall), yield penalties in non-CTF could be up to 40%. Yield results from the modelling work agree well with previous compaction (e.g. Refs. [108,109]) and CTF *vs.* non-CTF studies (e.g. Ref. [15]) showing that yield responses to compaction are dependent on the seasonal effect of weather. The standard deviation (SD) of modelled data points in Fig. 8A reflects significantly higher inter-annual yield variability in non-CTF (SD = 661 kg ha^{-1}) with less reliability of cropping compared with CTF (SD = 191 kg ha^{-1}) (SD values not shown in Fig. 8A).

Predicted yield penalties in non-CTF compared with CTF can be explained by reduced PAWC (Table 1) and the soil water balance as determined by differences between infiltration and runoff. The ability of the crop to extend a root system to access water and nutrients is also restricted in compacted soil [60,110]. In above-average rainfall years, crop yield is less constrained by rooting depth because water supply through rainfall is not a limiting factor. Therefore, in wet years, any reduction in infiltration or increases in runoff due to compaction would have less effect on water availability. By contrast, in average- and below-average rainfall years, reduced PAWC coupled with reduced rooting depth in compacted soil, as shown by Antille et al. [60], would have a significant effect on crop yield (Fig. 8A).

While the modelling study captured well the seasonal differences in crop performance and the impact on soil water due to compaction, the work relied on the selected runoff CN [18,75]. Despite this, the runoff CN selected for the current work appears to be appropriate based on previous studies that developed functional relationships between soil water infiltration and wheeling and rainfall energy [77]. Field investigations are needed to further adjust the selection of the appropriate runoff CN, or otherwise verify it for Red Ferrosols, in accord with the extent of soil compaction (including surface-sealing properties).

5.4. Economic considerations and drivers for adoption

Average gross margins (GM) across all fertiliser types show that additional AUD74 ha^{-1} may be realised in CTF compared with non-CTF + ZT, and about AUD150 ha^{-1} compared with non-CTF + ST (Table 3). Differences in GM between the two traffic systems will increase or decrease depending on the seasonal effect of weather, as predicted by the long-term yield-to-rainfall response relationships (Fig. 8A). However, a limitation of these analyses, not captured by the model, is the progressive recovery of soil structure (and consequently soil function) when traffic compaction is avoided in 85% of more of the cultivated field area, as shown by other studies (e.g. Ref. [20]). The major impact of CTF in subtropical environments with unreliable rainfall is through the overall improvement in soil water economy and conservation because of soil structure. Improved soil physical conditions translate into reduced risk of crop failure, or equally, increased frequency of successful crops (e.g., double- and inter-cropping), as well as lower inter-annual variability in crop yield. This has financial implications for the whole-of-farm system [111]. Other benefits of CTF over non-CTF, not captured by the modelling work, relate to the fact that field operations in CTF systems are performed within a rather structured environment [56]. This facilitates improved precision, in-field efficiency and trafficability (field access), which in turn improves the timeliness of field operations (planting, fertiliser application in-crop, crop protection and harvest) with lower energy-use [10].

The cost of full conversion to CTF, and the associated repayment period, may be determined as a function of the yield differential (ΔY) between CTF and non-CTF, as shown by Blackwell et al. [112]. Using Blackwell's analysis as an example, and long-term ΔY found within this work, the repayment period for full conversion to CTF would be less than 5 years if the cost of full conversion was up to about AUD600,000. The repayment period for conversion costs in Blackwell's analysis assumes 2800 ha per annum of wheat yielding 2000 kg ha^{-1}, and grain is priced at AUD0.25 per kg and 8.5% interest rate. If additional economic benefits could be realised as a result of increased grain quality (premium price) and other savings such as reduced input costs (precision management, fuel savings), the repayment period could be reduced by up to 50% [112]. This should be possible because (compacted) permanent traffic lanes enable more timely field operations (e.g., planting, spraying, fertiliser application, harvest) facilitating better crop husbandry. Acknowledgement of the multiplicative effects that result from coupling CTF, ZT and precision agriculture will serve to increase adoption of CTF in Australia; particularly, if the perceived economic and environmental benefits continue to be demonstrated at commercial-scale farming and through on-farm research [11].

6. Conclusions

This article has presented and discussed results of both field and modelling investigations into the short- and long-term effects of CTF on grain sorghum productivity and responsiveness to applied N fertilisers, and has quantified potential RUE and NUE gains that could be realised compared with non-CTF systems. The main conclusions derived from this work are:

1. Increased productivity and resource-use efficiency (N and rainfall) in CTF were mainly explained by avoidance of (random) traffic-induced compaction in that system, and to significantly lesser extent, by the choice of N formulation. The overall fertiliser type effect on yield and NUE was small relative to that of traffic. This was confirmed by differences in grain yield, yield components, and yield-to-N responses observed between CTF and non-CTF. Results also showed that RUE and NUE cannot be significantly increased if the mechanisation system does not protect the soil from traffic compaction, regardless of the

[5] Ishaq et al. [107]'s measurements were made on total biomass. We applied a harvest Index of 50% to convert to grain yield and be able to estimate the grain yield penalty in compacted soil.

N formulation used. Enhanced efficiency fertilisers, such as DMPP-treated urea, may help improve NUE, but within the constraints of the systems, determined in this case by the soil physical condition and the water-limited yield that is achievable.

2. It was shown that if N application rates were to be optimised in both traffic systems, a 44% higher N input in CTF would result in 90% yield increment (or $\approx 0.97 \times Y_{MAX}$) compared with non-CTF. This also confirmed that MERN is lower in a system where yield is constrained by soil compaction. Fertiliser NUE, expressed as apparent N recovery in grain, were 23.9% and 13.6% for CTF and non-CTF, respectively, assuming N application rates equivalent to the average MERN in both systems. Agronomic efficiencies (AE) were 11.4 and 9.6 kg kg^{-1} for CTF and non-CTF, respectively, also assuming N applied at the average MERN in both systems. Both efficiency metrics, and increased biomass returned to soil as crop residue, demonstrate higher potential of CTF to mitigate N losses relative to other mechanisation systems where field traffic is not confined to permanent traffic lanes.
3. Long-term simulations (55 years) showed RUE to be 8.2 kg mm^{-1} for CTF and 4.9 kg mm^{-1} for non-CTF. The impact of soil compaction (non-CTF) on grain yield was relatively higher on below-average (30th percentile) rainfall conditions compared with the effect observed for average and above-average (70th percentile) rainfall conditions. Runoff-rainfall simulations inferred that, in drier years ($\leq$330 mm in-crop), increased soil strength in non-CTF impairs root exploration of the subsoil, which affects nutrient uptake and yield. In wetter years ($\geq$450 mm in-crop), water infiltration, and subsequent movement down the profile, is restricted by compaction. Therefore, soil strength may also remain high at depth. The net result is reduced water and nutrient uptake, and partitioning, relative to the crop in CTF soil. Reduced infiltration in non-CTF increased runoff compared with CTF, as shown by simulated rainfall-runoff relationships, which has implications for nutrient, carbon and sediment losses.
4. The sustainability and productivity of sorghum in mechanised farming systems could be significantly improved by promoting greater adoption of CTF. Field experiments in this work showed significant yield improvements under CTF, and depending on the tillage system, gross margin improved by between AUD74 and AUD150 per ha compared with non-CTF. Long-term simulations further showed that the median grain yield can be improved by about 1200 kg ha^{-1} (or ≈35%) in CTF compared with non-CTF. Based on the assumptions made in the analyses, the median increase in long-term yields in CTF represents an additional gross income of ≈AUD280 per ha compared with non-CTF.

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Declaration of competing interest

No conflicts of interest were declared by the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2021.100111.

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