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Agronomic performance of wheat (Triticum aestivum L.) and fertiliser use efficiency as affected by controlled and non-controlled traffic of farm machinery

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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 and economic performance of winter 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) responses were obtained by applying urea (46% N), urea treated with 3,4-dimethyl pyrazole phosphate (DMPP), commercially known as ENTEC® urea (46% N), and urea ammonium nitrate (solution, 30% N) at rates between 0 (control) and 300 kg ha^{-1} N at regular increments of 100 kg ha^{-1} N. The results showed that the CTF system increased grain yield, total aboveground biomass, and harvest index by 12%, 9%, and 4%, respectively compared to the crop grown under the non-CTF system ($P<0.05$). Overall, the agronomic efficiency was 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; however, there was not fertilizer type effect on NUE. On average, the optimal economic nitrogen application rates and corresponding grain yields were 122 kg ha^{-1} and 3337 kg ha^{-1}, and 175 and 3150 kg ha^{-1} in the CTF and non-CTF systems, respectively. This work demonstrated that significant improvements in fertilizer-N recoveries may not be realized with enhanced nitrogen formulations alone and that avoidance of (random) traffic compaction is a pre-requisite for improved fertilizer use efficiency.*

Keywords. *Controlled traffic, DMPP, Enhanced N fertilizer formulations, Nitrogen use-efficiency, Soil compaction, Urea ammonium nitrate, Urea.*

Introduction

Controlled traffic farming (CTF) is a mechanization system in which tramlines and seed beds are distinctly and permanently separated to optimize conditions for trafficability with farm machinery as well as soil conditions for crop growth. 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 the 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, particularly for subtropical edaphoclimatic conditions. Therefore, work was undertaken to: (1) Determine the effect of traffic compaction on the yield-to-nitrogen response of winter wheat crops, (2) Determine the effect of such compaction on fertilizer use efficiency and quantify differences in fertilizer-use efficiency for controlled and non-controlled traffic systems, N fertilizer formulation, and derive the most economic fertilizer application rate, and (3) Determine the changes in the crop's gross margins under both traffic systems as a result of changes in the price of nitrogen fertilizers. This work also seeks to demonstrate that in terms of nitrogen use efficiency little can be gained from the use of enhanced fertilizer formulations (EEF) if soil conditions are such that crop agronomic performance cannot be optimized. This has practical implications for nitrogen management because much effort is being spent on optimizing the use of EEF, but no consideration has been given to the detrimental effects of traffic compaction on fertilizer use efficiency, with some exceptions (e.g., Tullberg et al., *submitted*).

Materials and Methods

Experimental site

The experiment was 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. 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.

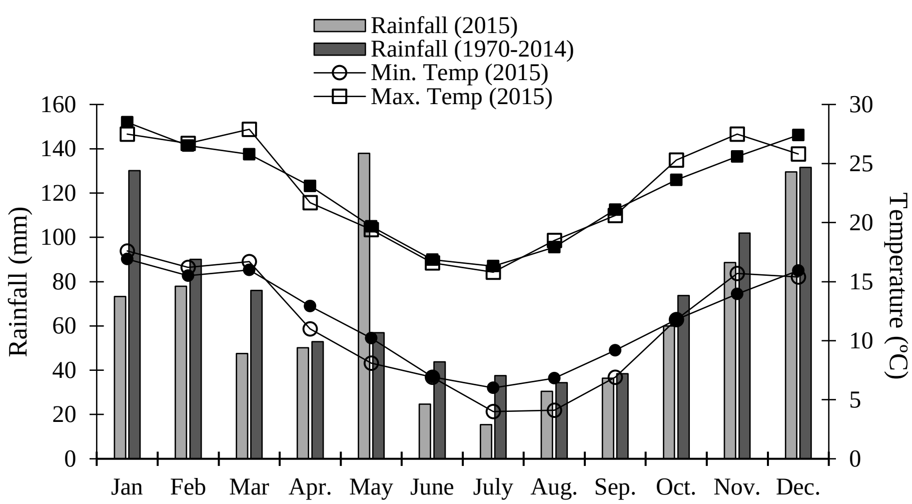

Figure 1. Rainfall and temperature records for the University of Southern Queensland at Toowoomba, Australia (after University of Southern Queensland, 2015).

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 (British Standards, 1990) 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 et al., 2015). 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.

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 an agricultural tractor (Belarus 920, 100 HP, gross mass: 3.9 Mg) driven at a speed of 5 km h^{-1}, fitted with 11.2-20 (front) and 15.5-38 (rear) tyres inflated to 35 and 26 psi, 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 et al., 2015) albeit on different soils. Soil moisture at the time of traffic was 18% and 20.5% (w/w) at the 0-200 mm and 200-400 mm depth intervals, respectively.

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. Phenological 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 crops in SE Queensland. A blanket 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 2). Cone penetrometer 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 digitally recording the force at 25 mm depth increments based on ASABE Standard EP542 (ASABE, 2013). Soil moisture content was simultaneously determined because of its influence on soil strength (Ayers and Perumpral, 1982). Measurements were conducted ten times (n=10) for each traffic treatment. 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 with respect to time to describe the relationship between the rate of infiltration and time. Measurements were replicated three times (n=3).

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) 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 phenological stages 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 hence N use efficiency (NUE). Differences in yield between fertilized and non-fertilized crops, relative to N applied as fertilizer were used to denote agronomic efficiency (Baligar et al., 2001). 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) (Galambošová et al., 2017). 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 fertilizer 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 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 (James and Godwin, 2003). 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, 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; Antille et al., 2015b). 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 this, 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, whereas 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 Equation (9a) by these relative percentages. This was considered to be a fair assumption based on earlier studies (e.g., Galambošová et al., 2017).

Results and Discussion

Soil physical properties

Soil penetration resistance determined for the 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. Differences in soil moisture content between the two traffic systems were small (P>0.05).

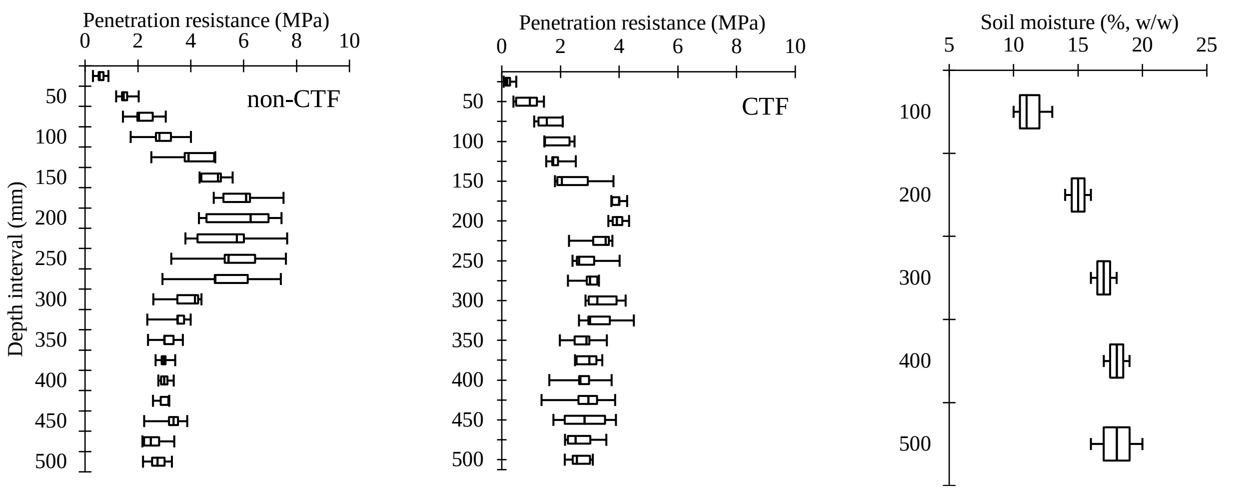

Figure 2. Soil penetration resistance and soil moisture content observed at the experimental sites for the CTF and non-CTF systems. For penetration resistance use P<0.05 (traffic treatments), and P>0.05 for soil moisture content.

Soil water infiltration rates for the CTF and non-CTF treatments are shown in Figure 3. Infiltration rates were significantly lower in non-CTF compared with CTF at any given time (P-values <0.05). Terminal infiltration rates in CTF were approximately double those of the non-CTF system.

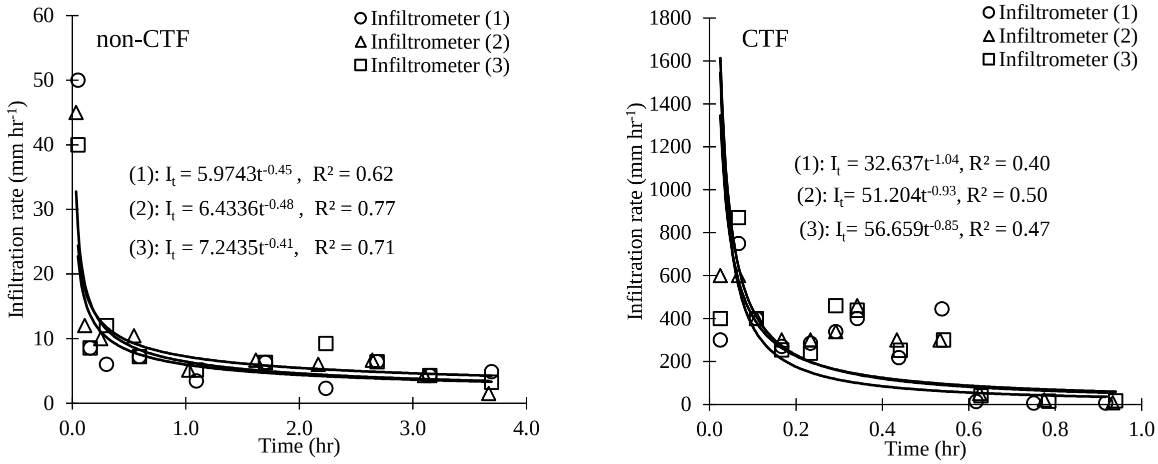

Figure 3. Relationship between infiltration rate and time recorded at the experimental site for the two traffic treatments. Use P<0.05.

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. 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 175 and 3028 kg ha^{-1} for CTF and non-CTF, respectively. Overall, there was not fertilizer type effect on grain yield, which suggested a relatively greater effect of compaction for all N-fertilizer formulations and N application rates. There was not fertilizer type × N application rate effect on grain yield (P>0.05). Despite this, the maximum yield was observed (3579 kg ha^{-1}) under the CTF system with UAN applied at a rate of 200 kg ha^{-1} N.

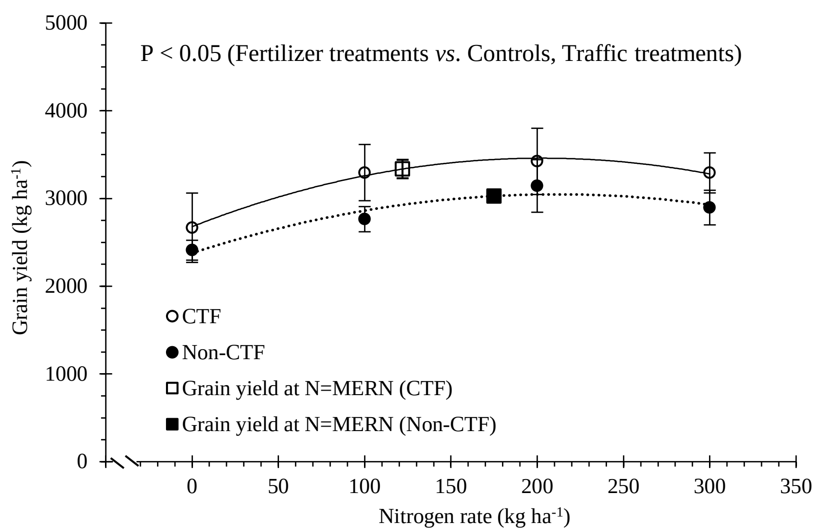

Figure 4. The relationship between nitrogen application rate and grain yield as affected by traffic of farm machinery. Error bars denote standard deviation (SD) of mean (n = 9, except for N=0 and N=MERN, n=3).

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 5). 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.

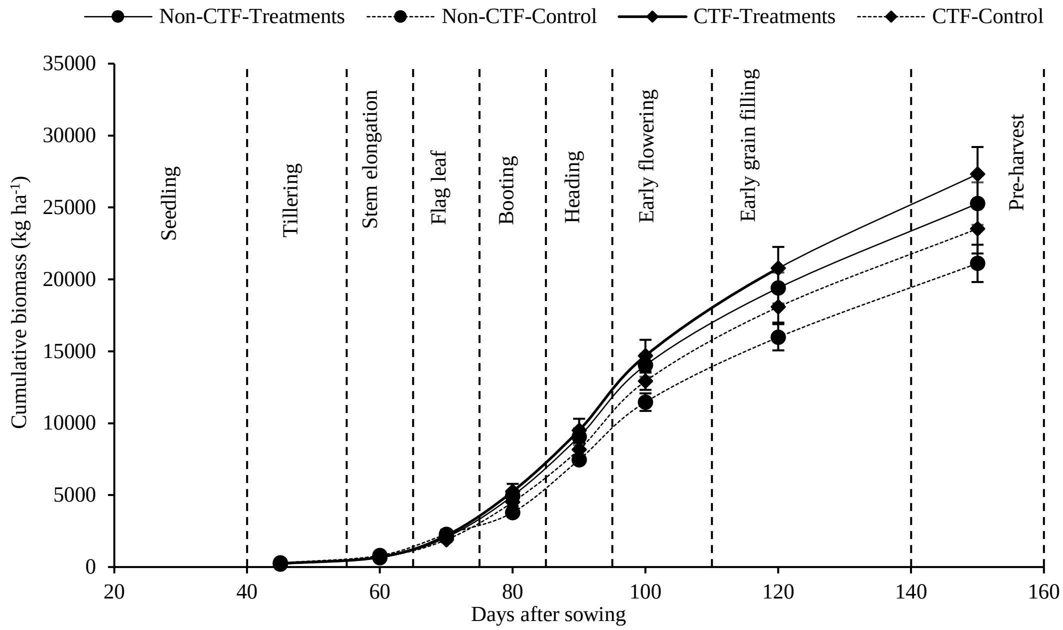

Figure 5. The effect of traffic compaction on cumulative aboveground biomass. Use n = 27 for treatments and n = 3 for controls). Error bars denote standard deviation of the mean. Crop growth stages are based on Zadoks et al. (1974).

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 6). Harvest indices were generally higher when fertilizer was applied at rates between 100 and 200 kg ha^{-1} N, which was in accord with estimates of optimum N application rates.

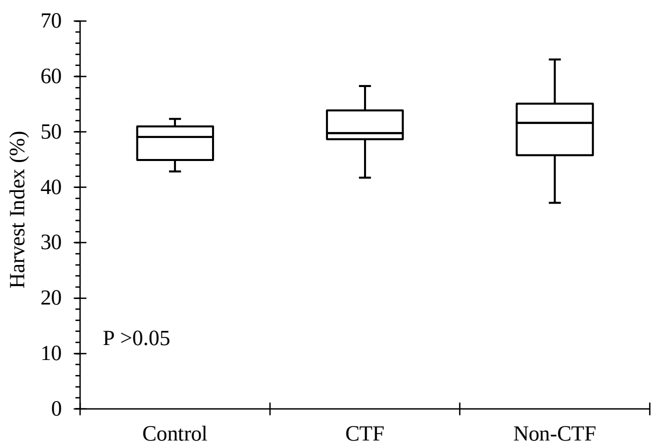

Figure 6. Harvest index as affected by controlled and non-controlled traffic of farm machinery. Box plots show Min, Q_1, Med, Q_3, and Max, respectively. Use n = 6 for Control (N = 0), and n = 27 for traffic treatments (N ≠ 0).

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 7).

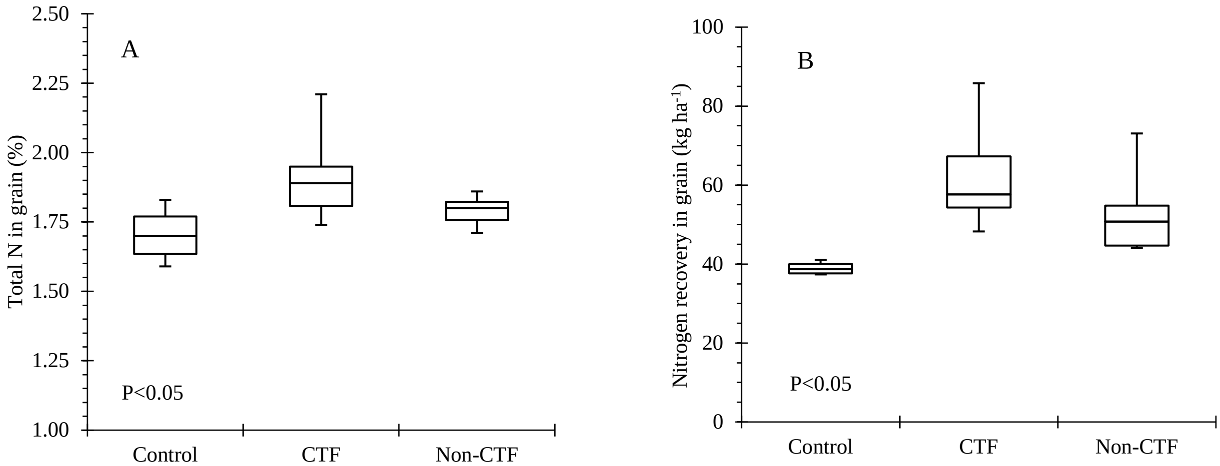

Figure 7. Traffic treatment effects on total grain-N (A) and N recovery in grain (B), respectively. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively. Use n = 6 for Control (N = 0), and n = 27 for traffic treatments (N ≠ 0).

Overall, the CTF system showed that NUE may be increased by up to 50% compared to non-CTF, which was significant ($P<0.01$) as shown in Figure 8. The fertiliser 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 conditions. The value of NUE that corresponds with the optimum N application rate was derived from the NUE-to-N rate response relationships shown in Figure 8. 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.

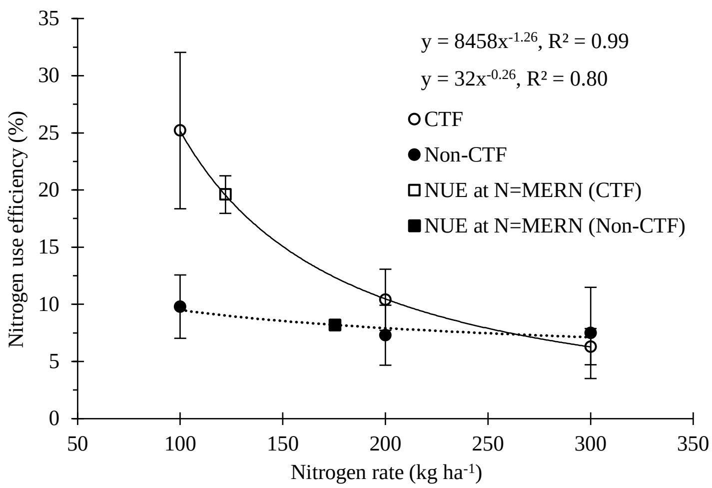

Figure 8. The relationship between N application rate and N use efficiency (NUE) for CTF and non-CTF. Error bars denote SD of mean (n=6, except n = 3 for N = 300 kg ha^{-1} and N=MERN). Use $P<0.05$.

Overall, agronomic efficiency (AE) was ≈35% higher in CTF compared with non-CTF (≈4 *vs*. 3 kg kg^{-1}, respectively), as shown in Figure 9. However, at the optimum N rate (MERN), the agronomic efficiency is approximately 50% higher in CTF compared with non-CTF ($P<0.01$). Similarly, there was not 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.

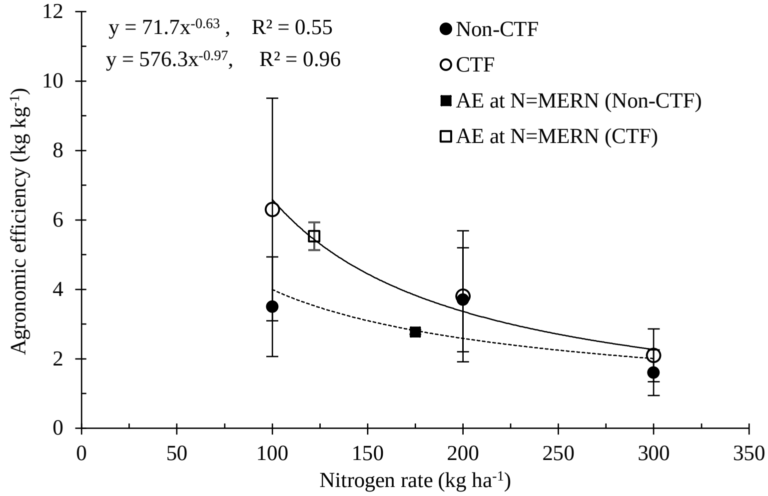

Figure 9. The relationship between N application rate and N use efficiency (NUE) for CTF and non-CTF. Error bars denote SD of mean (n=9, except n = 3 for N = MERN). Use P<0.05.

Most economic rate of nitrogen and gross margin

Table 3 shows the most economic rate of N (MERN) and corresponding yield (Y_{MERN}) calculations as derived from the yield-to-nitrogen response relationships, and price ratios (P_R) for the year of harvest. Yield-to-nitrogen responses were significant when a quadratic model was fitted to the data ($P<0.05$), which was observed in both traffic systems. For all fertilizer materials, responses were higher in CTF compared with non-CTF. Average gross margin (GM) calculations were approximately 11% higher in CTF compared to non-CTF (Table 4). Differences in gross margins between fertilizer types are mainly due to differences in the cost of N, particularly for ENTEC. The impact of fertilizer-N cost on gross margin was therefore higher for the non-CTF system because of overall lower yield.

Table 3. The most economic rate of nitrogen (MERN) for wheat and the theoretical application rate for maximum yield response (N_{MAX}) for CTF and non-CTF systems. Notation: (1) price of grain, (2) price of nitrogen, (3) price ratio, (4) standard error (5), maximum nitrogen application rate (6), maximum yield (7), most economic rate of nitrogen (8), crop yield at MERN.

Treatments		P_{Grain} (1)	P_N (2)	P_R (3)	Response	P-value	R^2-value	SE(4)	N_{Max} (5)	Y_{Max} (6)	N_{MERN} (7)	Y_{MERN} (8)
		(AUD kg^{-1})	(AUD kg^{-1})	- -	- - -	- - -	- - -	- - -	(kg ha^{-1} N)	(kg ha^{-1})	(kg ha^{-1} N)	(kg ha^{-1})
Non-CTF	UAN	0.28	0.77	2.8	$y = 1390.17 + 19.6x - 0.051x^2$	0.06	0.99	88	192	3273	165	3236
	ENTEC urea	0.28	0.96	3.4	$y = 1422.89 + 16.35x - 0.038x^2$	0.04	0.99	57	215	3182	170	3104
	Urea	0.28	0.75	2.7	$y = 1469.48 + 14.52x - 0.031x^2$	0.19	0.96	266	234	3170	191	3112
CTF	UAN	0.28	0.77	2.8	$y = 2681.6 + 9.22x - 0.0226x^2$	0.09	0.99	65	204	3622	143	3538
	ENTEC urea	0.28	0.96	3.4	$y = 2662.32 + 5.13x - 0.008x^2$	0.03	0.99	20	321	3485	106	3117
	Urea	0.28	0.75	2.7	$y = 2692.91+ 8.74x - 0.026x^2$	0.20	0.95	116	168	3427	117	3358

Table 4. Total variable cost (TVC) and gross margin (GM) obtained from winter wheat based on the MERN and Y_{MERN} presented in Table 3 (Rural Solutions SA, 2016). GI is gross income, use AUD1 ≈ USD0.75

Traffic treatment/Cost		Fertilizer	Seed	Operations	Agrochemicals	TVC	GI	GM
		AUD ha^{-1}	AUD ha^{-1}	AUD ha^{-1}	AUD ha^{-1}	AUD ha^{-1}	AUD ha^{-1}	AUD ha^{-1}
Non-CTF	UAN	168	20.3	27.1	97.1	312.4	935.7	623.3
	ENTEC urea	204	20.3	27.1	97.1	348.4	870.4	522.1
	Urea	184	20.3	27.1	97.1	328.4	895.5	567.2
CTF	UAN	151	20.4	27.1	97.1	295.4	982.4	687.1
	ENTEC urea	142	20.4	27.1	97.1	286.4	872.4	586.1
	Urea	128	20.4	27.1	97.1	272.4	933.5	661.2

Conclusions

The main conclusions derived from this work are:

- Controlled traffic farming (CTF) reduced soil cone index by 40% compared to non-CTF. In addition, CTF had a positive, significant effect on yield components, which therefore translated into higher yield (12%) compared to the non-CTF system. As a result, yield-to-nitrogen responses were significantly lower in non-CTF compared with CTF, which had implications for nitrogen recovery in grain and use efficiency.
- Gross margin analyses showed that for the crop established under CTF this was approximately 10% higher than non-CTF. Differences in gross margin between fertilizer types were mainly due to differences in the price of N as there was no fertilizer type effect on grain yield.
- The experimental results showed that it is unlikely that significant gains in fertilizer use efficiency could be achieved through the choice of N formulation alone, and that improved soil conditions such as that of a typical CTF system, are a pre-requisite for improved nutrient recovery in crop and crop yield.

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