

Article

# Assessing Controlled Traffic Farming as a Precision Agriculture Strategy for Minimising N<sub>2</sub>O Losses

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## Abstract

Intensive vegetable farming emits high nitrous oxide (N<sub>2</sub>O) due to traffic-induced compaction, highlighting the need for preventing nitrogen (N) losses through better traffic management. This study examined the effects of Controlled Traffic Farming (CTF) and Random Traffic Farming (RTF) on N<sub>2</sub>O emissions using intact soil cores (diameter: 18.7 cm; depth: 25 cm) collected from a vegetable production system in Pukekohe, New Zealand. Soil cores from CTF beds, CTF tramlines, and RTF plots were analysed under fertilised (140 kg N/ha) and unfertilised conditions. N<sub>2</sub>O fluxes were monitored over 58 days using gas chambers. The fertilised RTF system significantly ( $p < 0.05$ ) increased N<sub>2</sub>O emissions (5.4 kg N<sub>2</sub>O–N/ha) compared to the unfertilised RTF system (1.53 kg N<sub>2</sub>O–N/ha). The emission from fertilised RTF was 46% higher than the maximum N<sub>2</sub>O emissions (3.7 kg N<sub>2</sub>O–N/ha) reported under New Zealand pasture conditions. The fertilised CTF system showed a 31.6% reduction in N<sub>2</sub>O emissions compared to fertilised RTF and did not differ significantly from unfertilised CTF. In general, CTF has demonstrated some resilience against fertiliser-induced N<sub>2</sub>O emissions, indicating the need for further investigation into its role as a greenhouse gas mitigation strategy.

**Keywords:** Controlled Traffic Farming; denitrification; nitrous oxide; Random Traffic Farming; water-filled pore space



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## 1. Introduction

Agriculture plays a pivotal role in New Zealand's economy, accounting more than 50% of the nation's total export value [1]. Approximately 45% of the country's land area is allocated to agricultural use, of which 93% is managed under a pastoral system. The remaining portion is used for a diverse mix of annual and perennial cropping and horticultural practices [1]. The industry encompasses around 55 different crops and operates across approximately 50,000 hectares of land, primarily concentrated in regions such as Pukekohe, Hawke's Bay, Canterbury, and Gisborne [2]. These regions provide favourable climatic and soil conditions for year-round production of both field and greenhouse vegetables. Despite its productivity, the sector faces growing challenges related to land use intensification, environmental regulations, and climate variability (Ministry for Primary Industries [3]). Over

the past 20–30 years, significant land use intensification has occurred across New Zealand, resulting in various adverse environmental consequences, including soil compaction [4].

Soil compaction poses a critical challenge in New Zealand's intensive vegetable production, particularly in regions like Horowhenua, Pukekohe, and Canterbury, where frequent machinery use and short crop rotations are common. Soil compaction is a critical issue as it alters soil structure, reducing pore space and impeding oxygen diffusion. This promotes anaerobic conditions that facilitate the microbial process of denitrification, ultimately leading to the production of nitrous oxide ( $N_2O$ ) [5,6]. Nitrous oxide is of particular concern as it is both a potent greenhouse gas and an ozone-depleting substance [7,8]. In addition to this, it also represents a significant loss of applied N fertiliser, undermining both environmental sustainability and agricultural efficiency [9]. One study demonstrated that  $N_2O$  emissions could be up to four times higher in compacted soils compared to non-compacted soils [10]. This substantial increase is primarily attributed to reduced oxygen availability, which enhances denitrification, the principal biological pathway responsible for  $N_2O$  generation.

Topsoil compaction due to field traffic can increase  $N_2O$  emissions by 1.3 to 42 times, a process that is further exacerbated in the presence of high nitrogen (N) inputs due to enhanced conditions for microbial denitrification [11]. The influence of tractor compaction and N fertiliser rate on  $N_2O$  emissions from an irrigated potato crop was estimated in New Zealand, and it was reported that 2.5 to 2.9 kg  $N_2O-N/ha$  was emitted from the tractor-compacted furrows [12]. However, the emissions were only 0.4 to 1.2 kg  $N_2O-N/ha$  from either the ridges or uncompacted furrows. They also reported that the influence of tractor compaction on  $N_2O$  emissions was higher than the soil mineral N concentration at 70 to 90 kg N/ha. However, except this one known study, there is no information published in the literature on  $N_2O$  emission due to traffic-induced soil compaction in other vegetable cropping systems in New Zealand.

To address soil compaction, vegetable growers in New Zealand have increasingly adopted Controlled Traffic Farming (CTF), which is a precision agriculture strategy that minimises unnecessary soil disturbance. CTF operates as an in-field traffic management system, maintaining permanent separation between crop zones and traffic lanes through the integration of advanced technologies such as satellite navigation and auto-guidance systems [13,14]. Satellite navigation and auto-guidance systems play a key role in implementing CTF by ensuring the accurate and repeatable movement of machinery along permanent traffic lanes. These technologies help maintain consistent wheel paths, minimizing random trafficking and preserving soil structure in crop zones [15]. This spatial separation ensures that the crop zone remains uncompacted, leading to improved root growth and increased crop yields [16]. Simultaneously, the deliberate compaction of traffic lanes improves vehicle traction efficiency compared to conventional Random Traffic Farming (RTF) practices [17]. Additionally, CTF has been shown to improve soil physical properties by preserving porosity and aeration in the crop zone, creating a favourable environment for gaseous exchange [18,19].

$N_2O$  emissions have been shown to be significantly lower under CTF systems compared to RTF systems, with reductions of 45.4%, 21%, 24.8%, and 38.3% reported for spinach, sown onions, planted onions, and carrots, respectively [19]. After five years of partial CTF implementation, emission reductions in the crop zone ranged from 21% to 45% relative to RTF [19]. Emissions from trafficked soils were found to be consistently 2.2 times higher than those from non-trafficked soils [18], and simulated random traffic generated similar emissions to permanent traffic lanes but significantly higher emissions than those from non-trafficked crop beds [20]. Potential reductions in  $N_2O$  emissions from CTF systems were estimated to range between 20% and 45%, with at least a 20% reduction in direct

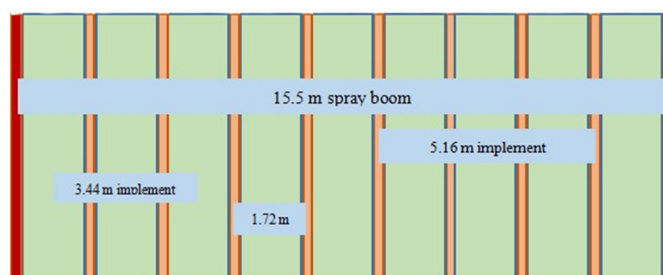
emissions from field operations compared to non-CTF systems [21]. Overall, total soil emissions could be reduced by 30% to 50% through the adoption of CTF, with consistent results across various soil types, crop rotations, and environmental conditions [22]. Therefore we hypothesize that implementing a CTF system will significantly reduce N<sub>2</sub>O emissions compared to RTF in New Zealand's intensive vegetable production systems. The prominent intervention highlighted in this study is the application of CTF as a strategic field management practice to mitigate N<sub>2</sub>O by reducing soil compaction and preserving soil physical structure in the crop zone.

Despite extensive evidence supporting the agronomic and environmental benefits of CTF, particularly in reducing N<sub>2</sub>O emissions, there remains a lack of empirical data quantifying these effects within New Zealand's vegetable-growing regions. Limited studies suggest that CTF implementation may contribute to mitigating N<sub>2</sub>O emissions while also alleviating traffic-induced compaction [18,19]. However, direct comparative measurements under New Zealand conditions are lacking. To address this research gap, the present study aimed to quantify and compare N<sub>2</sub>O emissions under CTF and RTF systems using soil cores collected from commercial vegetable fields in Pukekohe, New Zealand.

## 2. Materials and Methods

### 2.1. Study Area

This study was conducted in two commercial-scale vegetable plots in Pukekohe, New Zealand (37.3187° S, 174.9985° E). The soil is characterised as volcanic ash with dark reddish-brown clay-loam texture and slightly acidic to neutral soil pH. An area of 4 ha was managed under a CTF system, while an adjacent 4 ha plot was operated under an RTF system. The CTF plot comprised 130 established beds of a 1.72 m basic module width and 260 intermediate tramlines having a 0.24 m width (wheel tracks in between the beds). Tramline spacing typically occurred at approximately 1.72 m with a wheel gauge width of 1.72 m as the basic module. The distance between two permanent tramlines (spray line) at the plot was 15.5 m, which corresponds to 9 times the basic module width of 1.72 m (Figure 1). CTF techniques have been practised at this plot for a period of 10 years. All machineries used for tillage were run on defined traffic lanes (tramlines with reduced tillage on the CTF plot). The RTF plot was conventionally managed without designated wheel tracks or structured traffic paths, allowing unrestricted machinery movement across the field. The crops cultivated at the experimental site during the four years preceding the study included potatoes, oats, carrots, and grass.

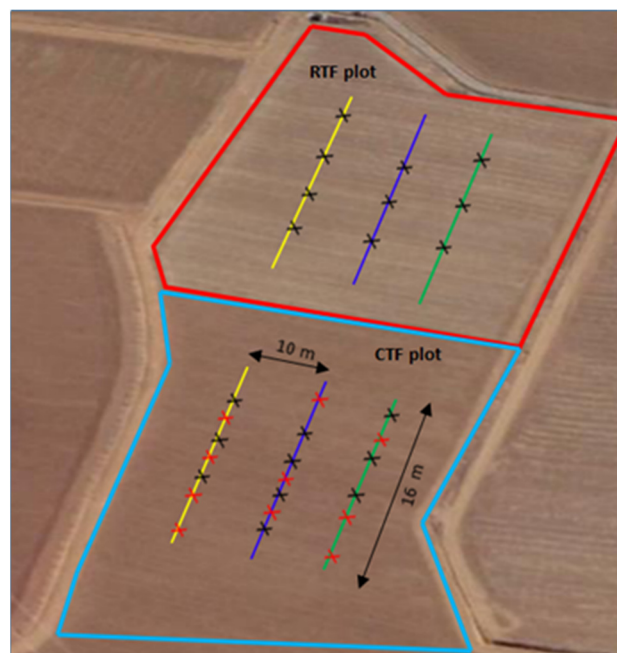


**Figure 1.** Machinery integration of 1.72 m track width with spray lines showing working widths as integer of basic module width in CTF system in Pukekohe.

### 2.2. Soil Core Sampling

Both the CTF and RTF fields were situated on sloped terrain. To account for topographical variation, each field was divided into three transects, namely upper, middle, and lower, spanning a horizontal distance of 16 m across the field. These transects included both crop beds and tramlines in the CTF system, whereas the RTF field was managed

without defined beds or tramlines. The lower transect was established at the bottom of the field, the upper transect was located at the top, and the middle transect was positioned equidistantly between the two. The horizontal distance between adjacent transects was 10 m. Soil core samples were collected along each transect in both fields (Figure 2).



**Figure 2.** Locations of random soil core sampling along the transects from CTF and RTF in Pukekohe ( $-37.3187^{\circ}$  S,  $174.9985^{\circ}$  E). Imagery date: 3 November 2016. Source: Adapted from Google Earth (2020).

Random undisturbed soil core samples were collected from CTF beds, CTF tramlines, and RTF plots [23]. Undisturbed soil cores were sampled using plastic cylinders of an internal diameter of 18.7 cm from CTF beds, RTF, and tramlines (TRM) along the upper, middle, and lower transects (Figure 2). Sampling transects are indicated by the solid yellow (lower transect), blue (middle transect), and green (upper transect) lines. Black crosses indicate soil core sampling locations at CTF beds and RTF along the lower, middle, and upper transects. Red crosses indicate soil core sampling locations on tramlines along lower, middle, and upper transects in CTF plots. In total, 30 soil cores (10 cores from each treatment location) were collected at a soil depth of 25 cm from the soil surface. This sampling depth was selected because significant differences in soil compaction were observed up to 25 cm, with minimal or no variation beyond this depth. Undisturbed soil cores were collected using plastic cylinders, driven into the soil to maintain the natural structure, porosity, and layering of the field soil. The cores were then sealed at both ends during transport to prevent moisture loss or disturbance.

### 2.3. Soil Core Experiments

Soil core experiments were conducted over a period of 58 days, starting from mid November 2020. The study evaluated relative  $N_2O$  emissions from three traffic systems of CTF, RTF, and CTF tramlines (TRM) in a vegetable production field in Pukekohe, New Zealand. The experiment included two rates of N application of 0 kg N/ha (unfertilised) and 140 kg N/ha (fertilised), resulting in six treatment combinations (Table 1) with five replicates. Specifically, 0.83 g of urea (46% N) was manually applied to each soil core, corresponding to a field-equivalent application rate of 140 kg N ha $^{-1}$ . The soil cores

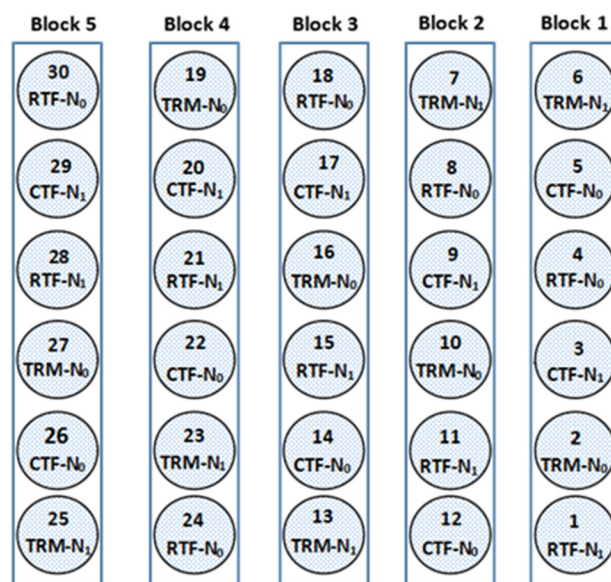
contained pre-established Tama grass (*Lolium multiflorum*) at the time of collection, as they were sampled directly from the field with intact vegetation.

**Table 1.** Treatment combinations of the soil core experiments.

Treatment	Description
CTF-N <sub>1</sub>	Controlled Traffic Farming + 140 kg N/ha
RTF-N <sub>1</sub>	Random Traffic Farming + 140 kg N/ha
TRM-N <sub>1</sub>	Tramline + 140 kg N/ha
CTF-N <sub>0</sub>	Controlled Traffic Farming + 0 kg N/ha
RTF-N <sub>0</sub>	Random Traffic Farming + 0 kg N/ha
TRM-N <sub>0</sub>	Tramline + 0 kg N/ha

N<sub>1</sub> denotes fertiliser application at a rate of 140 kg N/ha, while N<sub>0</sub> represents no fertiliser application.

The soil cores containing plastic cylinders were transferred to the Dairy No. 1 farm facility of Massey University, Palmerston North, on 16th November 2020 and were subsequently installed at a depth of 10 cm into the soil using a Randomised Complete Block Design (RCBD) as illustrated in Figure 3. The experiment utilised the existing stand of Tama grass that was already growing in the soil cores at the time of collection. The soil cores were installed in the field immediately after sampling. Nitrous oxide emissions from each core were evaluated using emission chambers over a 56-day period following fertiliser application. The soil cores were exposed to ambient environmental conditions, including natural rainfall and dry periods, to simulate field conditions. The cores were sealed only during gas sampling events to maintain airtight conditions for N<sub>2</sub>O flux measurements. A lid was placed on top of each soil core at the time of sampling to seal off a fixed volume of air in the headspace volume.



**Figure 3.** Field experimental lay-out of fertilised and unfertilised soil cores.

#### 2.4. Gas (N<sub>2</sub>O) Sample Collection and Analysis

Gas samples were collected twice weekly for one month following fertiliser application, and then weekly for an additional four weeks, during which N<sub>2</sub>O fluxes had returned to background levels. N<sub>2</sub>O was the sole gas measured in this study, as the primary objective was to identify a management strategy to minimise N fertiliser losses through denitrification. As a key intermediate and indicator of denitrification processes, N<sub>2</sub>O measurement alone was considered sufficient to address the study's aim. CO<sub>2</sub> and CH<sub>4</sub>

emissions were not assessed in this study, as they are not directly influenced by N fertiliser application and do not reflect fertiliser-derived N losses.

Sampling was conducted using the static chamber technique. Gas samples were drawn from the airtight headspace, which was equipped with a three-way stop valve, using a 12 mL pre-evacuated syringe. Three consecutive gas samples were collected at a predetermined sampling interval of 45 min (0, 45, and 90 min). The sampling time was restricted between 10 am and 1 pm to avoid large temperature fluctuations during sampling. At each sampling time, the air within the soil cores was aerated by drawing air into the syringe and expelling it twice. Continuous soil temperature measurements were recorded using temperature sensors placed both inside and outside the soil cores, and at a depth of 2 cm below the soil surface. Gas samples were transported to the laboratory and analysed for N<sub>2</sub>O concentrations using the Shimadzu GC-2010 gas chromatograph. The N<sub>2</sub>O flux rates were calculated based on the rate of change in N<sub>2</sub>O concentration within the headspace of the soil cores, which was estimated as the slope of linear regression between N<sub>2</sub>O concentration and time [24]. Daily flux rates were estimated from the linear increase in headspace gas concentration over time. The N<sub>2</sub>O flux on a particular day was calculated using the following equation:

$$F = \frac{d_c}{d_t} \times \rho \times H \quad (1)$$

F is the N<sub>2</sub>O flux ( $\mu\text{g N m}^{-2}\text{h}^{-1}$ );  $\frac{d_c}{d_t}$  is the increment in the headspace in one hour ( $\mu\text{L L}^{-1}$ );  $\rho$  is the N<sub>2</sub>O gas density ( $\text{gm}^{-3}$ ); and H is the soil core height (m).

The resulting flux rates were then integrated over the measurement period using the trapezoidal rule to estimate cumulative emissions. The integrated flux was converted to a per-hectare basis and expressed as kg N<sub>2</sub>O/ha over the defined period.

### 2.5. Weather Data

Daily rainfall, evapotranspiration, air temperature, RH, wind speed, and mean daily air temperature for the entire experimental period were obtained from the NIWA data base [25]. Water-filled pore space (WFPS) for the entire period was simulated using the NIWA water balance model [25] with the initial and final moisture content measured from the soil cores at the beginning and end of the experiment.

### 2.6. Grass Harvesting and Analysis for N Uptake

Grass was harvested three times during the experiment, with the 1st cut being made 14 days after planting grass. The 2nd and 3rd cuts were made 20 and 41 days after the 1st cut, respectively. The total N uptake by the plants was determined by digesting 0.1 g of sub-sample from each treatment using the micro-Kjeldahl digestion method. The total N concentration was then analysed using a Technicon Autoanalyser, Series 2 [26]. The total N uptake of the plants was estimated as the product of dry matter yield and plant N concentration (%).

### 2.7. Soil Analysis

At the end of the 56-day experiment, bulk density and total residual N content of all soil cores were determined at 10 cm depth. Total residual inorganic N content was determined by extracting soil samples with 2 M KCl. The soil samples were passed through a 2 mm sieve and homogenised. About 3 g of moist soil was weighed into screw-capped centrifuge bottles and added to 30 mL of 2 M KCl. Sub-samples of the soil were oven-dried at 105 °C to determine the moisture factor. The centrifuged bottles were shaken on an end-over-end shaker for one hour and then centrifuged at 1118× g for 10 min, and the

supernatant was filtered through No. 42 Whatman filter paper. The  $\text{NO}_3^-$ -N and  $\text{NH}_4^+$ -N concentrations were analysed using a Technicon Autoanalyser [27].

$$N_{\text{inorganic}} = \frac{C \times V}{W} \quad (2)$$

where N is the total inorganic N content (mg/kg dry soil); C is the N concentration of soil extract (mg/L); V is the volume of solution (KCl + soil moisture) (L); and W is the mass of oven-dried soil (kg).

The amount of inorganic N accumulation (N<sub>min</sub>, kg N/ha) was calculated by

$$N_{\text{min}} = \frac{T \times \rho_b \times N_{\text{inorganic}}}{10} \quad (3)$$

where T is the soil thickness (cm);  $\rho_b$  is the soil bulk density ( $\text{g}/\text{cm}^3$ ); and N<sub>inorganic</sub> is the soil inorganic N content, which is defined as the sum of  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N (mg/kg).

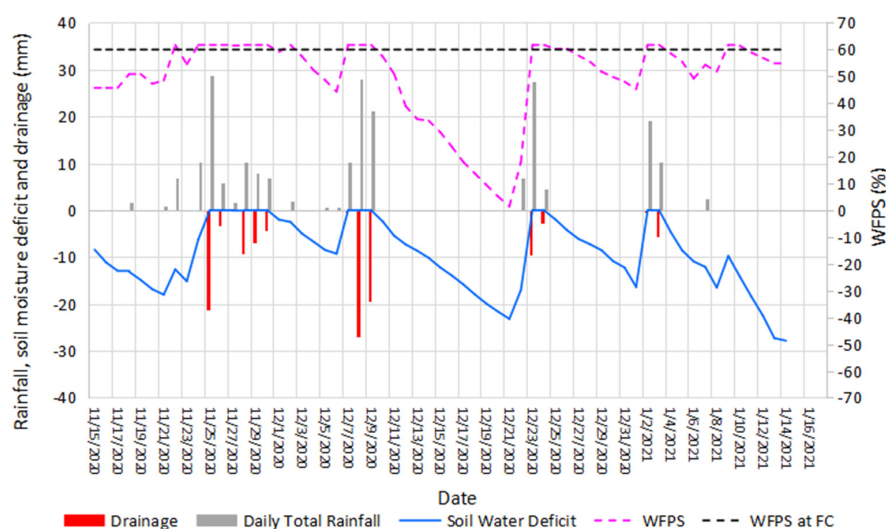
### 2.8. Statistical Analysis

The Anderson–Darling test for normality was conducted using Minitab 19.1.1, and the data did not meet the assumption of normality ( $p < 0.05$ ). Therefore,  $\text{N}_2\text{O}$  flux data were  $\log_{10}$ -transformed before performing further analyses. Two-way ANOVA with the PROC GLM procedure was used to test the main effects of traffic systems and fertiliser as well as their interaction effects on  $\text{N}_2\text{O}$  flux and grass yield using SAS version 9.4 [28]. A post hoc Tukey's test was performed to compare the treatment means at  $p < 0.05$ .

## 3. Results

### 3.1. Climate

A total of 22 precipitation events occurred during the sampling period. Rainfall started the day after urea application and continued for a week, followed by a drought period lasting for 12 days. Soil temperature fluctuated from 17.5 to 27.8 °C and averaged 20.8 °C during the experimental period. The simulated WFPS values derived from the NIWA water balance model ranged from 45.7% to 61.7% across all treatments, with an average of 48.9%. During the periods from 16th to 23rd November and 11th to 22nd December 2020, the WFPS values were below the critical threshold of 60% which is considered optimal for denitrification and elevated  $\text{N}_2\text{O}$  emissions (Figure 4).



**Figure 4.** Simulated water-filled pore space % (WFPS) in the soil cores from the traffic systems at 0 to 5 cm depth over the 58 days of the experimental period as per the NIWA water balance model.

In the present study, no significant differences in N<sub>2</sub>O emissions were observed between CTF and RTF systems. Post-experimental soil core analysis revealed no significant effect of traffic systems on soil bulk density. Consequently, the resulting soil porosities and moisture levels across CTF and RTF treatments were statistically not significant (Table 2).

**Table 2.** Status of bulk density and porosity in the cores at 0 to 10 cm depth.

Treatment	Mean Bulk Density (g/cm <sup>3</sup> )	Porosity
CTF-N <sub>1</sub>	0.81	0.69
RTF-N <sub>1</sub>	0.83	0.69
TRM-N <sub>1</sub>	0.87	0.66
CTF-N <sub>0</sub>	0.77	0.71
RTF-N <sub>0</sub>	0.76	0.67
TRM-N <sub>0</sub>	0.87	0.67
<i>p</i> value	ns	ns

ns, not significant at  $p < 0.05$  ( $n = 5$ ).

### 3.2. Initial and Final Soil Inorganic N Content

Both gravimetric soil moisture contents and the total residual N contents across all the soil cores were statistically similar at the beginning of the experiment. The total soil N (NO<sub>3</sub><sup>-</sup> + NH<sub>4</sub><sup>+</sup>) at the beginning of the experiment was less than 7 kg N/ha within the 0–25 cm depth across all soil cores. The soil residual N content in the upper 10 cm of the soil for the corresponding 8-week post-fertilisation period shows that the inorganic N content in the fertilised treatments was significantly higher ( $p < 0.05$ ) compared to the unfertilised treatments (Table 3). Soil inorganic N was recorded in the range between 34 and 56 kg N/ha at the depth of 10 cm in the fertilised soil cores, while it remained below 2 kg N/ha in all the unfertilised soil cores from different traffic systems. In both fertilised and unfertilised soil cores, the inorganic N content exhibited no significant variation across the traffic systems (Table 3).

**Table 3.** Initial moisture content and mean residual inorganic N content at 10 cm soil depth in Pukekohe clay loam across treatments.

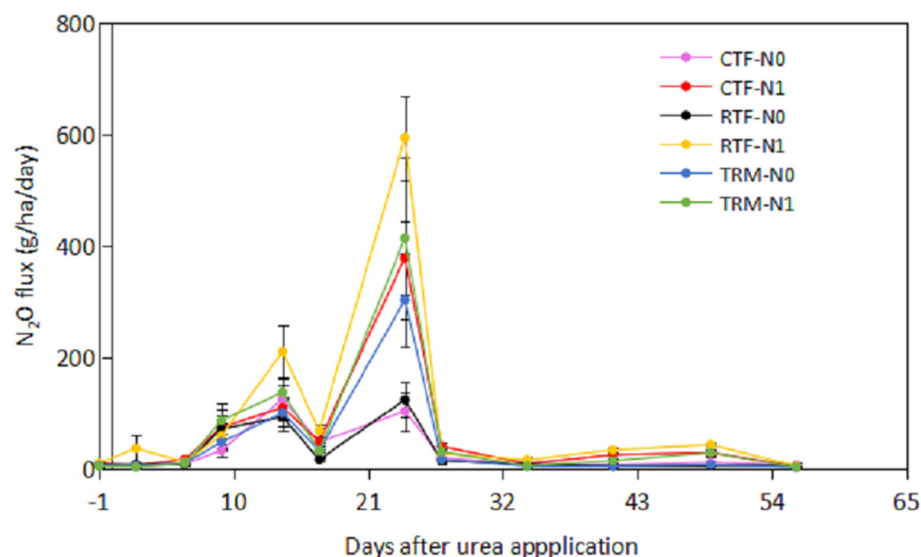
Treatment	Initial Gravimetric Water Content (g/g soil)	Initial Residual Inorganic N (kg N/ha)	Final Residual Inorganic N (kg N/ha)
CTF-N <sub>1</sub>	0.25 ± 0.02	5.81 ± 2.05	34.04 ± 14.28 a
RTF-N <sub>1</sub>	0.23 ± 0.02	3.29 ± 0.10	43.52 ± 7.47 a
TRM-N <sub>1</sub>	0.22 ± 0.01	2.51 ± 0.40	56.03 ± 11.98 a
CTF-N <sub>0</sub>	0.23 ± 0.02	6.80 ± 4.30	1.92 ± 0.32 b
RTF-N <sub>0</sub>	0.25 ± 0.01	3.49 ± 0.30	1.86 ± 0.33 b
TRM-N <sub>0</sub>	0.2 ± 0.02	2.46 ± 0.35	1.71 ± 0.38 b
<i>p</i> value	ns	ns	<0.0001

Data are mean ± standard error. Different letters indicate significant differences between depths at  $p < 0.05$  using Tukey's test ( $n = 5$ ).

### 3.3. Traffic System–Fertiliser Nitrous Oxide Emission Profile

The N<sub>2</sub>O fluxes obtained from all the cores before urea application denote that the background N<sub>2</sub>O fluxes were ranging from 4.86 to 10.3 g N<sub>2</sub>O–N ha/day. Nitrous oxide fluxes showed an increase only from RTF-N<sub>1</sub> with emissions of 36.6 g N<sub>2</sub>O–N/ha/day within two days of urea application. All the treatments showed two major distinct N<sub>2</sub>O–N peaks at 14 and 24 days following urea application, where the emissions from RTF-N<sub>1</sub> were the highest, with 210.1 and 594.2 g N<sub>2</sub>O–N/ha/day, respectively. Nitrous oxide fluxes from

all treatments returned to background levels 24 days after urea application and remained low for the rest of the experiment (Figure 5).



**Figure 5.** Daily N<sub>2</sub>O flux as influenced by traffic systems (CTF, RTF, and TRM) and N fertiliser (urea). Error bars show standard error ( $n = 5$ ).

The first notable peak in N<sub>2</sub>O emissions occurred 14 days post-fertilisation, following two rainfall events of 28.8 mm and 5.8 mm on 25th and 26th November, respectively. These precipitation events raised the WFPS to 61.7%, with values remaining elevated until 30th November (Figure 4). On the 14th day, WFPS was recorded at 59.2%, which is close to the threshold above which denitrification becomes a dominant process. A second emission peak was detected 24 days after fertilisation (11th December), which was more pronounced in fertilised cores (Figure 5). At this point, WFPS had declined to 50.9%, which was lower than the 60% threshold (Figure 4).

The integrated N<sub>2</sub>O emission profile revealed that the fertilised CTF system (CTF-N<sub>1</sub>) did not significantly increase emissions compared to its unfertilised counterpart (CTF-N<sub>0</sub>). Daily N<sub>2</sub>O emission was significantly higher ( $p < 0.05$ ) in fertilised RTF (RTF-N<sub>1</sub>) two days after urea application relative to all other treatments (Table 4). Fertilised CTF (CTF-N<sub>1</sub>) treatments showed significant differences ( $p < 0.05$ ) from their unfertilised counterparts except at 24 and 41 days after urea application. However, RTF-N<sub>1</sub> showed significantly higher ( $p < 0.05$ ) emissions than its unfertilised counterpart at 2, 17, 24, and 41 days after urea application. The TRM-N<sub>1</sub> treatment showed significantly higher emission only at 41 days after urea application. Mean integrated emissions of 5.4 kg N<sub>2</sub>O/ha were recorded from RTF-N<sub>1</sub>, which was significantly higher by 253% ( $p < 0.05$ ) than the emissions from RTF-N<sub>0</sub> (Table 4). The integrated N<sub>2</sub>O flux over the experimental period reveals that the traffic systems did not show any impact on N<sub>2</sub>O emissions. However, the CTF-N<sub>1</sub> treatment resulted in a 31.6% reduction in emissions compared to the RTF-N<sub>1</sub> treatment.

**Table 4.** Effect of traffic system on daily and integrated N<sub>2</sub>O emissions over the experimental period.

Treatments	Days After Urea Application												Integrated flux (kg N/ha)
	−1	2	6	9	14	17	24	27	34	41	49	56	
	g N <sub>2</sub> O/ha/day												
CTF-N <sub>1</sub>	9.08 a	5.85 b	17.07 a	74.43 a	109.88 a	49.29 ab	378.52 ab	37.89 a	9.56 ab	25.33 ab	29.36 a	4.57 ab	3.69 abc
RTF-N <sub>1</sub>	10.3 a	26.3 a	12.96 a	59.61 a	210.16 a	68.69 a	594.27 a	30.6 ab	16.46 a	34.10 a	43.33 a	5.2 a	5.40 a
TRM-N <sub>1</sub>	4.86 a	3.12 b	9.98 a	86.88 a	137.15 a	32.40 ab	414.39 ab	30.2 ab	5.44 ab	14.85 b	29.16 a	2.82 ab	3.99 ab
CTF-N <sub>0</sub>	8.25 a	4.25 b	8.92 a	33.11 a	125.2 a	48.12 ab	103.57 c	15.6 ab	8.09 ab	7.13 c	11.47 b	3.87 ab	1.41 c
RTF-N <sub>0</sub>	7.79 a	7.92 b	8.42 a	71.74 a	92.99 a	16.63 b	124.08 bc	12.22 b	8.27 ab	5.36 c	5.94 b	3.64 ab	1.53 c
TRM-N <sub>0</sub>	6.12 a	5.67 b	10.26 a	47.93 a	100.41 a	33.29 ab	303.35 ab	20.49 ab	4.65 b	4.34 c	7.64 b	2.31 b	2.49 bc

Mean values with different letters within a column indicate significant differences between treatments at  $p < 0.05$  using Tukey's test ( $n = 5$ ).

### 3.4. Grass N Uptake

Grass N uptake was significantly affected by both N application ( $p < 0.00001$ ) and traffic treatments ( $p < 0.01$ ) at the time of 2nd grass cut, but neither the traffic nor fertiliser affected at the 1st cut. Nitrogen uptake was affected by fertiliser treatment not by traffic at the time of 3rd cut. Overall, total N uptake across treatments was significantly higher ( $p < 0.05$ ) for all the fertilised traffic treatments compared to the unfertilised counterparts (Table 5). However, the N uptake from CTF and RTF were not statistically significant regardless of N fertiliser application. The N uptake from TRM-N<sub>1</sub> was not different from that of CTF-N<sub>1</sub> and RTF-N<sub>1</sub> but the N uptake from TRM-N<sub>0</sub> was significantly lower ( $p < 0.05$ ) from CTF-N<sub>0</sub> treatment.

**Table 5.** Effect of traffic systems on the N uptake (kg N/ha) of grass over the soil core experimental period.

Treatments	1st Cut	2nd Cut	3rd Cut	Total N Uptake
	14 dys after planting grass	20 days after 1st cut	41 days after 1st cut	
CTF-N <sub>1</sub>	5.10 a	19.08 a	11.24 abc	35.42 a
RTF-N <sub>1</sub>	5.84 a	16.25 ab	12.47 ab	34.57 a
TRM-N <sub>1</sub>	3.54 a	17.88 a	15.99 a	37.41 a
CTF-N <sub>0</sub>	2.48 a	11.27 bc	6.29 bcd	20.06 b
RTF-N <sub>0</sub>	3.75 a	7.20 cd	3.08 cd	14.04 bc
TRM-N <sub>0</sub>	4.43 a	1.58 d	0.59 d	6.46 c

Mean values with different letters within a column indicate significant differences between treatments at  $p < 0.05$  using Tukey's test ( $n = 5$ ).

## 4. Discussion

### 4.1. Effect of Traffic System on N<sub>2</sub>O Fluxes

Soil aeration, governed by bulk density and water content, plays a pivotal role in N<sub>2</sub>O emissions, with higher bulk density typically reducing oxygen diffusion and potentially promoting denitrification-driven emissions [29,30]. The absence of statistically significant differences in bulk density and porosity across traffic treatments (CTF, RTF, TRM) suggests that the imposed traffic regimes did not substantially alter soil compaction. The narrow range of bulk density values (0.76 to 0.87 g cm<sup>-3</sup>), with porosity remaining above 0.66 across all treatments, is generally considered sufficient to maintain aerobic conditions and limit denitrification-driven N<sub>2</sub>O emissions [31]. These findings are consistent with previous research indicating that moderate variations in bulk density do not necessarily lead to elevated N<sub>2</sub>O fluxes unless relative gas diffusivity approaches a critical threshold (~0.006) [32].

The similarity in porosity between CTF and RTF treatments further supports the notion that traffic-induced compaction effects may be buffered under certain soil conditions, suggesting that traffic intensity is insufficient to induce measurable changes in the soil [33]. Furthermore, certain soils exhibit natural resilience to compaction, which can also maintain uniform physical properties even under mechanical stress [34]. This inherent resilience may have contributed to the stability of the soil structure and gas exchange pathways in the soil cores, further explaining the lack of a treatment effect on N<sub>2</sub>O emissions.

The 31.6% reduction in N<sub>2</sub>O emissions from the fertilised CTF (CTFF-1) treatment is consistent with previous findings from organic vegetable farming in the Netherlands, where CTF was shown to reduce N<sub>2</sub>O emissions by 20–50% [19]. The reduction was attributed to the seasonal control of wheel traffic, which preserved soil structure and minimised compaction in trafficked zones, thereby enhancing aeration and reducing conditions favourable

for denitrification. The reduced emission reduction in our CTF system can similarly be attributed to better preservation of soil structure and reduced subsurface compaction in CTF, which enhances gas diffusivity and oxygen availability [35]. However, these improvements were not sufficient in soil cores to produce statistically significant differences in N<sub>2</sub>O emissions.

The elevated cumulative N<sub>2</sub>O emissions observed under the RTF treatment (5.4 kg N<sub>2</sub>O ha<sup>-1</sup>) appear to be primarily driven by the application of urea fertiliser. This finding demonstrates that increases in N<sub>2</sub>O fluxes are significantly amplified only when N fertiliser is present, suggesting that soil compaction alone exerts minimal influence on N<sub>2</sub>O emissions unless accompanied by enhanced N availability [36–38]. Mechanistically, this enhancement may be attributed to the synergy between reduced gas diffusivity under increased substrate availability for microbial nitrification and denitrification processes following fertiliser application [39,40]. Particularly in trafficked field systems, the temporal proximity of N input appears critical, with peak N<sub>2</sub>O emissions typically occurring within days of urea application due to rapid hydrolysis and subsequent nitrate formation [41].

#### 4.2. Effect of WFPS on N<sub>2</sub>O Fluxes

The observed consistency in water-filled pore space (WFPS) across traffic treatments indicates that vehicular compaction had a limited effect on soil moisture dynamics during the study period. This suggests that traffic-induced changes in soil structure did not substantially alter the soil's water retention capacity. The sub-threshold WFPS levels observed during the periods from 16th to 23rd November and 11th to 22nd December 2020 imply that denitrification was likely constrained, and N<sub>2</sub>O emissions were predominantly driven by nitrification pathways. This aligns with findings that N<sub>2</sub>O production via denitrification becomes dominant only when WFPS exceeds 60–70%, depending on soil type and microbial community structure [42]. Similarly, previous studies reported that peak N<sub>2</sub>O fluxes typically occur when WFPS surpasses 65%, reinforcing the moisture sensitivity of denitrification-driven emissions [42–44].

The temporal pattern of N<sub>2</sub>O emissions observed in this study closely reflected the combined effects of soil N availability and moisture dynamics. No substantial increase in N<sub>2</sub>O emissions was observed until six days after urea application (Figure 5). This delay was expected in the unfertilised treatments, where emissions were likely constrained by low residual soil N levels (Table 2). In the fertilised cores, however, the initially delayed emissions may be attributed to the dry spell that occurred between 16th and 23rd November 2020, resulting in a soil water deficit of 11.1 to 15.2 mm (Figures 4 and 5). This finding aligns with the fact that fertiliser applications during dry weather often result in negligible N<sub>2</sub>O losses due to insufficient moisture for microbial activity and gas production [45,46].

The first notable peak occurred 14 days post-fertilisation, coinciding with two rainfall events (28.8 mm and 5.8 mm on 25th and 26th November, respectively), which elevated the WFPS to 61.7%. Although WFPS on the 14th day was recorded at 59.2%, slightly below the commonly cited denitrification threshold of 60%, the sustained wet conditions likely facilitated the formation of anaerobic microsites, thereby promoting denitrification-driven N<sub>2</sub>O emissions [42,44]. At the second emission peak, detected 24 days after fertilisation, the WFPS had declined to 50.9%, which is a level considered sub-optimal for denitrification but conducive to nitrification processes. Under these moderately aerobic conditions, N<sub>2</sub>O emissions were likely driven by autotrophic nitrification pathways [47–49]. Previous studies have shown that nitrification is a significant source of N<sub>2</sub>O when WFPS ranges between 35% and 60%, with peak emissions often occurring near 50–55% WFPS due to optimal oxygen availability [47,48]. This alternation between wet and dry soil conditions

during the experimental period, as reflected by WFPS fluctuations, likely triggered shifts in microbial pathways responsible for N<sub>2</sub>O production.

#### 4.3. Effect of N Fertiliser on N<sub>2</sub>O Fluxes

The integrated N<sub>2</sub>O emission profiles in this study demonstrate a potential buffering effect of these traffic-managed configurations on soil denitrification processes. These findings are partially consistent with previous work in winter wheat systems, where fertiliser applied at 80 kg N ha<sup>-1</sup> did not result in significantly higher N<sub>2</sub>O emissions from RTF zones compared to tramlines [20]. Such results underscore the importance of strategic fertiliser placement within traffic-managed systems as a means to suppress emission hotspots and enhance N use efficiency.

Absence of elevated emissions from fertilised TRM treatments suggests that the interactions among N inputs, soil moisture, crop uptake, and N dynamics collectively influence the soil microbial processes responsible for N<sub>2</sub>O generation [50]. Although CTF-N<sub>1</sub> in our study did not show a statistically significant reduction in emissions compared to fertilised RTF, it resulted in a 31.6% reduction in cumulative N<sub>2</sub>O emissions. This reduction is comparable to the 22.4% and 42.7% emission reductions previously reported for CTF systems with varying traffic intensities (12% and 100% wheeled area, respectively) when compared to RTF systems with a 50% and 100% wheeled area [18]. Given that our CTF system had 13% traffic lanes with 100% wheel coverage, the 31.6% emission reduction indicates a notable improvement in soil physical conditions under CTF and reflects effective mitigation potential.

When benchmarked against data from New Zealand, where N<sub>2</sub>O emissions under ryegrass pasture range between 0.45 and 3.74 kg N<sub>2</sub>O ha<sup>-1</sup> [51], the emissions from our CTF and TRM treatments fell within a similar range (Table 6). However, the fertilised RTF treatment (RTF-N<sub>1</sub>) showed significantly higher emissions of 5.4 kg N<sub>2</sub>O ha<sup>-1</sup>, exceeding the upper threshold of pasture-based emissions by 46% and indicating a 253% increase compared to its unfertilised counterpart (RTF-N<sub>0</sub>), which emitted 1.53 kg N<sub>2</sub>O ha<sup>-1</sup> (Table 4). These elevated emissions highlight the potential risks associated with fertilised RTF systems.

**Table 6.** Comparison of N<sub>2</sub>O emissions with emissions reported from soils under pasture in New Zealand.

Treatments	Total Emissions from This Study (kg N <sub>2</sub> O/ha)	Reported Emissions from Other Studies (kg N <sub>2</sub> O/ha)
CTF-N <sub>1</sub>	3.69	0.45 [52]
RTF-N <sub>1</sub>	5.40	3.74 [42]
TRM-N <sub>1</sub>	3.99	2.40 [50]
CTF-N <sub>0</sub>	1.41	0.78 [18]
RTF-N <sub>0</sub>	1.53	
TRM-N <sub>0</sub>	2.49	

The lack of a significant increase in N<sub>2</sub>O emissions following fertiliser application under the CTF system suggests that it may help maintain favourable soil physical conditions that limit denitrification potential. The absence of compaction-related increases in bulk density likely preserved soil aeration, thereby reducing the formation of anaerobic microsites responsible for N<sub>2</sub>O production. These findings support the possibility that CTF systems help moderate N<sub>2</sub>O emissions, although the extent of their effectiveness may depend on environmental factors. However, it is too early to evaluate the function of CTF in N<sub>2</sub>O mitigation as this study was based on a single-season soil core experiment. Long-term, multi-season field studies are needed to validate these findings.

#### 4.4. Nitrogen Uptake and N<sub>2</sub>O Emissions

The lack of significant grass cover at the beginning of the study, along with the low N uptake of 4.2 kg N/ha within two days after urea application, indicates that plant N uptake had a minimal impact on N<sub>2</sub>O emissions during the initial phase. In this context, the significantly higher N<sub>2</sub>O emissions of 26.3 g N<sub>2</sub>O–N/ha/day from RTF-N<sub>1</sub> underscore the role of the RTF system in amplifying N<sub>2</sub>O emissions when fertilised (Table 4). Despite the increasing N uptake by growing vegetation, our study found no consistent inverse relationship between N uptake and N<sub>2</sub>O emissions across treatments. As vegetation gradually established over the subsequent days, increased plant N uptake may have masked the effects of traffic-induced soil physical changes on N<sub>2</sub>O emissions. This trend aligns with findings from previous studies, which emphasise that plant N uptake is a key determinant of soil N availability and subsequent gaseous losses in temperate agricultural systems [53]. Moreover, variations in vegetation cover and growth dynamics can significantly influence both the magnitude and temporal variability of N<sub>2</sub>O emissions [54]. These findings suggest that the increasing influence of vegetation through N uptake and canopy development became more prominent as the study progressed.

## 5. Conclusions

N<sub>2</sub>O emissions were mainly driven by fertiliser application, with traffic treatment having no significant effect. Although cumulative emissions did not differ significantly between CTF and RTF systems, the fertilised CTF treatment resulted in a 31.6% reduction compared to fertilised RTF, which recorded the highest emission level of 5.4 kg N<sub>2</sub>O ha<sup>-1</sup>, underscoring the emission risks associated with nitrogen fertiliser use. These findings are indicative, as field-based experiments in Pukekohe could not be conducted due to travel restrictions imposed during the coronavirus pandemic, and this study was therefore carried out as a pot experiment. Under the given soil and environmental conditions, traffic-induced changes in bulk density and moisture appeared minimal, suggesting that the soils may possess a degree of structural resilience that limits compaction-related impacts on N<sub>2</sub>O emissions. The soil core experimental setup may have limited the representation of complex field interactions. Therefore in situ studies are needed to comprehensively assess the impact of CTF on N<sub>2</sub>O emissions.

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## Abbreviations

The following abbreviations are used in this manuscript:

CTF	Controlled Traffic Farming
RTF	Random Traffic Farming
WFPS	Water-Filled Pore Space
N <sub>2</sub> O	Nitrous Oxide
N	Nitrogen

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