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Short communication

Controlled traffic farming effects on soil emissions of nitrous oxide and methane

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ABSTRACT

Soil compaction affects soil aeration and gas diffusivity, and thus has a major impact on the release of greenhouse gases (GHGs) from fertilised soils. Controlled traffic farming (CTF) systems reduce the area of compacted soil by confining all field traffic to permanent traffic lanes, and a pilot trial at one long-term CTF site provided evidence of reduced soil emissions. We investigated the effect of CTF on soil emissions of nitrous oxide (N_2O) and methane (CH_4) using replicated manual chamber measurements in 3 traffic treatments; namely: non-trafficked CTF beds, permanent CTF lanes, and a single traffic pass on CTF beds to simulate the random traffic tracks of non-controlled traffic farming. Emissions of N_2O and CH_4 were monitored from these treatments in 15 crops over 3 years on 6 grain farms in Queensland, Victoria and Western Australia. This work has demonstrated that N_2O emissions from trafficked soil were consistently and significantly greater (by an average factor of 2.2) than those from non-trafficked soil. At the same time, soil CH_4 consumption was significantly increased in the CTF beds compared to random-trafficked or permanent traffic lanes, although overall CH_4 fluxes were small. Permanent traffic lanes normally represent only 10%–15% of field area on controlled traffic farms, compared with ~50% or more trafficked area on non-controlled traffic farms. Thus, the results indicate that adoption of controlled traffic could reduce total soil emissions by 30%–50%. This demonstrates that CTF will reduce soil emissions of N_2O and CH_4 from mechanised crop production, while providing other agronomic, environmental and economic benefits.

1. Introduction

Nitrous oxide (N_2O), a powerful greenhouse gas, is produced in the soil by a number of processes. The largest is normally microbiological denitrification, which occurs when both nitrate and a carbon source are available, and aeration is restricted (Mosier, 1994). This commonly occurs when water-filled pore space (WFPS) is in the range 65–80% (Dalal et al., 2003). WFPS levels are high during intense rainfall events, and afterwards decline with drainage and evapotranspiration. Traffic compaction effects are most damaging to larger, vertically-oriented drainage pores, so infiltration and internal drainage rates are reduced (Vomocil and Flocker, 1961). Compaction reduces pore space and root exploration is also restricted (Barraclough and Weir, 1988), so WFPS levels decline more slowly after rainfall on compacted soil. The outcome is that soil affected by traffic compaction remains at high WFPS levels for longer, resulting in more anaerobic sites where denitrification can occur (Berisso et al., 2012), which consequently increases the risk of elevated soil N_2O emissions (Yamulki and Jarvis, 2002). In addition, it has been shown that reduced gas diffusivity from compaction inhibits soil CH_4 oxidation (Sitaula et al., 2000).

Several studies (e.g Ball, 2013) have demonstrated this correlation between soil compaction, N_2O emissions and CH_4 uptake, and Rochette (2008) has noted its relevance to the negative effect of no-till on N_2O emissions from some soils. With increasing adoption of no-till (Derpsch et al., 2010), the issue is significant because N_2O is a powerful greenhouse gas for which there are no significant terrestrial sinks. Agricultural activities contribute approximately 70% of all anthropogenic N_2O emissions (Davidson, 2009), largely from the nitrogenous fertiliser applications required to maintain or increase food production.

Traffic-induced soil compaction can be a problem in extensive no-till systems because tractor and harvester axle loads in the range 7–25 Mg are common and traffic covers 15–20% of crop area in all field operations except spraying and spreading. The problem is exacerbated because soil is usually moist at seeding, and sometimes still moist at depth at harvest time, when traffic impacts can often be detected at > 400 mm depth (Ansorge and Godwin, 2007). Varying implement

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widths and traffic gauges normally ensure that traffic patterns are essentially random, so approximately 50% of field area is likely to be compacted in each cropping cycle (Kroulik et al., 2009) and the whole field area will be compacted over time, in the absence of mechanical or natural amelioration. The recent adoption of more precise field guidance systems will have improved, but not eliminated this outcome in non-controlled traffic cropping.

Controlled traffic farming (CTF) systems use equipment of modular working width and traffic gauge, together with precise guidance to confine all load-bearing traffic to permanent lanes occupying 10–15% of paddock areas (ACTFA, 2017). This allows the other 85–90% of paddock area to self-ameliorate, or prevents re-compaction of rigid soils where deep tillage has relieved compaction. Widespread adoption of precise (nom. ± 25 mm) "GPS autosteer" for farm machinery, and increasing flexibility in equipment wheel (or belt) traffic gauge and operating widths has facilitated CTF adoption in the Australian grain industry. This is commonly based on a 3 m traffic gauge for all heavy equipment (tractors, sprayers, harvesters and seed, fertiliser and grain bins), and 9 m or 12 m operating widths for seeders and harvesters, usually combined with 27 m or 36 m sprayers and spreaders.

CTF provides a range of productivity benefits, which include greater rainfall infiltration rates, increased available water capacity and biological activity of non-trafficked soil in CTF beds. It also provides management benefits of reduced energy inputs and improved ease and timeliness of field access on permanent traffic lanes (Tullberg et al., 2007). This has led to increased adoption in Australian dryland grain production, and CTF was used on 21% of the Australian grain crop area according to GRDC (2015). It is also being adopted or explored by small numbers of innovative farmers operating other cropping systems (e.g. sugar cane and cotton, Antille et al., 2016) and in other countries (Chamen, 2015; Galambošová et al., 2017).

CTF also provides environmental benefits by reducing run-off, soil erosion and nutrient loss (e.g. Wang et al., 2008; Rohde et al., 2012). Broader environmental effects of CTF have been reviewed by Antille et al. (2015), who noted the positive effects on soil carbon balance, and a complimentary relationship between controlled traffic and the absence of mechanical compaction relief in no-till cropping.

Exploration of CTF emission effects is relatively recent: Vermeulen and Mosquera (2008) confirmed the positive emission effects of "seasonal" controlled traffic compared with random traffic in organic vegetable production, where seasonal CTF was applied in-crop after preseeding tillage. Tullberg et al. (2011) subsequently reported preliminary trial results showing that GHG emissions from permanent traffic lanes and non-permanent "random" trafficked clay soil were greater than those of no-till CTF beds under grain cropping by factors of between 3 and 4.

The evidence thus suggests that CTF might be a useful way to reduce emissions from crop production, but little is known of the magnitude of its effects, or its application on other soils and in other climatic conditions. Precise determination of total emissions requires more intensive monitoring than was economically feasible in a project to demonstrate a CTF effect on emissions across a wide range of Australian grain production areas over several years. Thus, the major objective was to determine the emissions of N_2O and CH_4 from random trafficked and permanent traffic lane soil, relative to those from non-trafficked CTF beds. These emission ratios are referred to here as traffic impact factors.

2. Materials and methods

Monitoring sites were established on 6 extensive grain growing farms using CTF (Fig. 1). Two sites were in Queensland, where a summer-dominant rainfall pattern and warmer winter temperatures allow frequent double-cropping. In the heavy clay soils of Queensland all fertiliser is normally drilled at or prior to the seeding operation, and permanent lanes are usually left unplanted. Three sites were established on CTF farms in Victoria and one in Western Australia. Annual cropping predominates in these southern regions with winter rainfall patterns and cooler temperatures, where permanent traffic lanes are usually seeded to prevent erosion of the lighter soils. Some fertiliser is applied at seeding, and N fertiliser top-dressing is broadcast as required. More site information, including fertiliser inputs and the number of years of CTF operation at each of the 15 sites can be found in Table 1.

CTF fields always have heavily-trafficked permanent traffic lanes and non-trafficked beds, but for the purposes of this experiment an additional "random" wheeltrack was imposed on the permanent crop beds to mimic traffic impact in non-controlled (random) traffic farming. This was installed during the seeding operation, when growers were asked to make a single tractor and seeder unit pass along a 50 m length of crop bed, 0.8-1.0 m away from the permanent lanes, with all soil-engaging components lifted clear of the soil. This was carried out immediately before seeding the site normally, travelling on the permanent lanes, leaving two seeded 0.48–0.65 m wide "random" wheeltracks on the permanent beds.

This layout was used on all sites with minor variations depending on grower equipment. It provided 2 sets of the 3 treatments with space for 4 replicate chambers (2 on each wheeltrack) with minimum additional traffic damage to the long-term non-trafficked cropping beds of controlled traffic farms. In all cases, the site was positioned on permanent traffic lanes that would not be required for in-crop spraying or fertiliser spreading operations, which normally use every 3rd set of permanent traffic lanes.

GHG fluxes were measured using the closed chamber technique (Chadwick et al., 2014) and quality criteria as outlined by de Klein and Harvey (2012), and Parkin and Venterea (2010). This method uses a gas-tight chamber, which encloses a fixed surface area of soil for a given time interval. The chamber consists of a frame driven 80–100 mm into the soil and a headspace or lid that is fixed to the frame during sampling periods, but removed at other times. Chamber enclosure is achieved by a sealed gasket at the lower edge of the lid.

Chambers of 2 types were used during this work:

- Cylindrical chambers: these were 400 mm lengths of 220 mm diameter plastic pipe, the bottom edge of which was chamfered on the outside to facilitate insertion to a depth of 80–100 mm. Tight-fitting lids could be installed during sampling periods, and these were fitted with a 4 mm diameter pipe and on/off tap for gas sampling.
- Rectangular chambers: these had a 450 × 650 mm base, 100 mm deep, fabricated from 2 mm stainless steel to fit the removable head spaces. The head spaces were 50 l rectangular white plastic crates fitted with a septum for gas sampling with a hypodermic syringe. Head spaces were located on the base by stainless steel lugs and retained by strong elastic cords to partially compress a 12 mm polyurethane foam sealing strip. The rectangular chambers normally spanned at least one crop row.

The 12 chamber bases were positioned as soon as possible after seeding, with 4 replicate chambers in each treatment, where the treatments represented permanent non-trafficked CTF beds, permanent CTF traffic lanes, and random-trafficked soil. Only one chamber type was used within any one site, and chamber positioning was consistent with respect to crop rows across all planted treatments, to ensure similar relationships with seed and fertiliser bands. Neither chamber type was expected to significantly influence in-crop fertiliser distribution to the enclosed area.

Emissions were monitored by placing and sealing headspaces or lids on the chamber bases and collecting air samples from the head spaces. After sealing, 4 samples were taken at 20 and 30 min intervals respectively, from the cylindrical and rectangular chambers. Samples (20 ml) were drawn into gas-tight 20-ml polypropylene syringes and transferred into evacuated vials ("Exetainers®). Chamber temperature was monitored during the measurement using an electronic

Fig. 1. Emission monitoring sites.

temperature sensor, and the gas samples later analyzed for N_2O and CH_4 concentrations using a gas chromatograph (Shimadzu GC-2014, Kyoto, Japan). Emission rates were calculated from the slope of the linear increase (N_2O) or decrease (CH_4) in concentrations within the closed chambers over the closure time (60 or 90 min for cylindrical and rectangular chambers, respectively). All fluxes were corrected for air temperature and pressure, adjusted for chamber volume, and expressed on an elemental weight basis for both N_2O (μg N_2O-N m^{-2} h^{-1}) and CH_4 (μg CH_4-C m^{-2} h^{-1}) (Scheer et al., 2013).

Sampling was carried out by local agricultural consultants, and the protocol requested weekly sampling for 6 weeks following seeding with 2 more weekly samplings carried out after fertiliser top-dressing, always subject to considerations of site access. Outside those periods, additional samplings were requested after > 20 mm rain, or if soil approached waterlogging, and at least one sampling was requested for later in the crop cycle when soil was significantly drier. The sampling protocol was influenced by economic considerations, and sampling frequency varied from 8 to 18 times per site, with an average of 14 samplings per cropping season. This low sampling intensity might be expected to underestimate emissions (Parkin, 2008; Smith and Dobbie, 2001), but sampling was also biased towards the earlier, higher-emission part of the season, which is likely to have the opposite effect.

Absolute values of total emissions determined by this low-intensity monitoring process might be of low reliability, but the ratio of mean emissions from different treatments should be a satisfactory indicator of treatment traffic impact factors. When CTF replaces non-CTF random traffic farming, the emissions reduction (TC – ratio) will depend on the proportion of field area previously compacted by random traffic (AR) and the proportion of field area occupied by permanent traffic lanes (AL) in the CTF system, in addition to the traffic impact factors (i.e. emissions relative to non-trafficked CTF beds) of each traffic treatment. If TL and TR are the respective traffic impact factors of permanent traffic lanes and random-trafficked soil, and the non-wheeled area of non-CTF fields is regarded as equivalent to CTF bed then:

$$TC = \frac{(TL \times AL) + (1 - AL)}{(TR \times AR) + (1 - AR)} \quad (1)$$

In the northern grain region (Queensland), emissions were monitored during 6 subtropical cropping cycles over 3 years, which included 4 winter and 2 summer crops at 2 experimental sites. In the southern region, 9 temperate winter cropping cycles were monitored over 3 years; 3 each at sites near Inverleigh and near Horsham and 1 at Swan Hill (Victoria). Sampling was also carried out over 2 years near Esperance (Western Australia).

2.1. Statistical analyses

Statistical analyses of GHG emissions data were undertaken with GenStat Release 16th Edition (VSN International Ltd., 2013), and involved ANOVA. 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 the data was not required.

3. Results

Treatment effects are shown here as the cumulative sum of N_2O and CH_4 emissions with rainfall data over the cropping season. Fig. 2A

Table 1
Site Details and Mean N2O-N and CH4-C Emissions, All Sites and Years.

Southern Region Sites									
Site		Inverleigh	Inverleigh	Inverleigh	Horsham	Horsham	Horsham	Esperance	Esperance
Year		14	15	16	14	15	16	15	16
System		2 m/6 m	3m/12	3 m/12	3 m/12 m	3 m/12 m	3 m/12 m	3 m/9 m	3 m/9 m
Soil Type		Sandy clay loam			Grey clay			Sandy loam	
Years in CTF		5	11	12	8	9	10	11	12
Crop		Wheat	Barley	Wheat	Wheat	Wheat	Wheat	Barley	Wheat
GSR	mm	185	165	522	90	91	308	175	447
Seeding	Date	25-05-14	26-05-15	7-05-16	12-05-14	20-05-15	22-05-16	18-05-15	12-05-16
N Input	Seeding	64	120	18	18	14	15.3	42.5	42.9
Top Dress	Date	12-8-14	13-8-15	12/8-11/10	18-7-14	0-1-00	12-8-16	28-7-15	6-7-16
	Top Dress	69	36.8	97	34.5	0	50.4	38	25.3
	Total N	133	156.8	118	52.5	14	65.7	80.5	68.2
Harvest	Date	21-12-14	8-12-15	19-12-17	30-11-14	23-11-15	15-1-17	10/12/ 2016*	11-12-16
Yield	t/ha	4.1	4.33	7.8	0.78	1	4.9	5.4	6.5*
2. Monitoring Pocesss, Duration and Mean Daily Emissions, N_2O, CH_4 andCO_2-e									
Samplings		18	18	22	8	12	12	14	11
Final Sample Date		17-12-14	19-10-15	7-11-16	#######- ##	2-10-15	17-11-16	25-08-15	23-09-16
Sampled Days		206	146	184	116	135	179	99	134
Mean N_2O-N Emissions	Random	8.472	3.201	3.6000	5.760	5.404	7.3728	8.505	20.95
g ha^{-1} d^{-1}	Lane	7.056	3.890	3.2544	1.440	5.436	4.9872	6.441	11.21
	Bed	1.704	1.953	2.0160	1.416	2.128	3.6888	3.331	9.4
Mean CH_4-C Emissions	Random	−0.528	0.353	−0.1920	−1.270	1.104	−0.6720	0.595	0.478
g ha^{-1} d^{-1}	Lane	−0.773	0.113	0.0240	−1.236	1.364	−1.5360	0.178	−0.287
	Bed	−1.378	−1.025	−1.0560	−2.966	−2.856	−2.5680	−0.818	−5.573
Total GWP* kg CO_2-e	Random	3.947	1.510	1.678	2.653	2.566	3.428	4.000	9.820
ha^{-1} d^{-1}	Lane	3.277	1.824	1.524	0.634	2.588	2.284	3.020	5.237
	Bed	0.753	0.881	0.909	0.567	0.904	1.644	1.532	4.219
N_2O Traffic Impact	Random	4.97	1.64	1.79	4.07	2.54	2.00	2.55	2.23
Factor	P.Lane	4.14	1.99	1.61	1.02	2.55	1.35	1.93	1.19
GWP Traffic Impact	Random	5.24	1.71	1.85	4.68	2.84	2.09	2.61	2.33
Factor	P.Lane	4.35	2.07	1.68	1.12	2.86	1.39	1.97	1.24

Southern Region Sites			Northern Region Sites						
Site	Swan Hill		Toowoomba	Toowoomba	Toowoomba	Toowoomba	Felton	Felton	
Year	16	Southern Region Site Means	13/14	15	15/16	16	14	15	Northern Region Site Means
System	3 m/13.7 m		3 m/9 m	3 m/9 m	3 m/9 m	3 m/9 m	3 m/9 m	3 m/ 9m	
Soil Type	Sandy Loam		Cracking black clay						
Years in CTF	2		12	13	14	15	6	7	
Crop	Barley		Sorghum	Barley	Sorghum	Barley	Wheat	Barley	
GSR	191	242	260	175	260	237	95	129	192.7
Seeding	13-05-16		18-09-13	14-05-15	10-10-15	13-07-16	16-06-14	27-05-15	
N Input	16	39	82	100	120	89	64	60	85.8
Top Dress	25-05-16		/	/	/	/	/	/	
	23	42	All applied at seeding or pre-applied						
	39	81	82	100	120	89	64	60	85.8
Harvest	12-12-16		5-3-14	1-11-15	11-3-16	28-11-16	19-11-16	4-11-15	

Table 1 (continued)

Site	Southern Region Sites: Swan Hill		Northern Region Sites: Toowoomba	Toowoomba	Toowoomba	Toowoomba	Felton	Felton	
Yield	4.48	4.10	3.8	3.5	7	5	2.03	2.04	3.9
2. Monitoring Pocesss, Duration and Mean Daily Emissions, N_2O, CH_4 andCO_2-e									
Samplings	8	13.7	15	14	12	14	14	15	14.0
Final Sample Date	24-09-16		1-03-14	13-11-15	7-03-16	2-11-16	12-10-14	29-10-15	
Sampled Days	134	148.1	164	183	149	112	118	155	146.8
Mean N_2O-N Emissions g ha^{-1} d^{-1}	6.1368	7.711	3.720	3.526	4.416	3.48	1.939	2.954	3.339
	6.9216	5.626	3.144	3.373	3.826	4.4	1.833	2.885	3.243
	4.0296	3.296	2.088	1.914	3.552	1.66	1.042	1.459	1.952
Mean CH_4-C Emissions g ha^{-1} d^{-1}	1.3704	0.138	−1.082	−0.526	−3.846	−0.44	0.204	0.068	−0.937
	1.0272	−0.125	−0.859	0.004	−2.682	−0.26	1.008	0.061	−0.455
	−0.9000	−2.127	−1.548	−2.005	−5.184	−1.9	−0.773	−0.980	−2.065
Total GWP* kg CO_2-e ha^{-1} d^{-1}	2.918	3.613	1.705	1.633	1.939	1.614	0.914	1.385	1.532
	3.272	2.629	1.444	1.579	1.704	2.051	0.890	1.352	1.503
	1.857	1.474	0.927	0.831	1.495	0.716	0.463	0.651	0.847
N_2O Traffic Impact Factor	1.52	2.59	1.78	1.84	1.24	2.10	1.86	2.02	1.81
	1.72	1.95	1.51	1.76	1.08	2.65	1.76	1.98	1.79
GWP Traffic Impact Factor	1.57	2.77	1.84	1.97	1.30	2.26	1.98	2.13	1.91
	1.76	2.05	1.56	1.90	1.14	2.87	1.92	2.08	1.91

* Based on GWP Values of 298 and 25 respectively for nitrous oxide and methane.

illustrates a large CTF impact (2014 winter wheat at Inverleigh, Victoria) and Fig. 2B a smaller impact (2013/14 summer sorghum at Toowoomba, Queensland). At these sites, and at all sites monitored in this work the sum of N_2O emissions from the random treatment was significantly greater ($P < 0.05$) than that measured from the non-trafficked permanent crop beds. At most sites, mean N_2O emissions from the CTF lane were rather less than, but not significantly different ($P > 0.05$) from those of the random treatments, but in 3 cases CTF lane emissions were closer to those of the CTF bed. At all sites and years, CTF beds demonstrated net uptake of CH_4, which was sometimes absorbed and sometimes emitted by random traffic and permanent lane and treatments. Overall, traffic treatment effects on CH_4 emissions were significant ($P < 0.05$) at all sites and years, and more CH_4 was always taken up by CTF beds than by either trafficked treatment.

Site, soil, years in CTF, and total growing season rainfall is set out in Table 1, along with crop, grain yield and fertiliser N inputs with the number of samplings and duration of monitoring (seeding – final sampling). Emission data is also included as the overall mean N_2O-N and CH_4-C emissions (Σfluxes/samplings, expressed in g ha^{-1} d^{-1}) for each treatment. Total Global Warming Potential (GWP) of these emissions has also been calculated using GWP factors of 298 and 25 for N_2O and CH_4, respectively (Department of the Environment and Energy, 2016) and expressed in kg CO_2-e ha^{-1} d^{-1}. These data illustrate the variability of conditions, inputs and sampling intensity between sites, as well as the variability of emissions.

Means of the data are given separately for the 9 southern sites, the 6 northern sites, and all 15 sites. In each case, the effect of random and permanent lane traffic treatments is also summarised as the Traffic Impact Factor, the ratio of GWPs of traffic treatments to that of the permanent, non-trafficked CTF crop beds. Net emissions from random-trafficked soil were consistently and significantly greater than those of non-trafficked beds, with an overall mean impact factor of 2.45. Emissions from permanent traffic lanes were more variable, sometimes not significantly different to non-trafficked beds, but with a mean impact factor of 2.01. Impact factors were generally greater in the southern region.

4. Discussion

CTF generally reduces wheeled area of paddocks to a value between 10% and 15%, but attempts to quantify the impact of CTF must define the area of traffic compacted soil in previous 'random' systems. 50% has often been assumed for Australian no-till grain production, based on the areas normally wheeled in a single cropping cycle of seeding, spraying, spreading, harvesting and grain handling operations, and supported by (unpublished) surveys of equipment dimensions. Emission calculations based on this assumption often imply that the other 50% is non-compacted and has emission characteristics similar to beds, which might be the case in soils where wetting and drying cycles, shrink/swell soil properties and biological activity can produce amelioration to a depth of about 100 mm over one year (McHugh et al., 2009). In no-till systems on rigid soils, however, seeder disturbance and biological activity (crop roots and soil biota) are the only ameliorating influences and wheel traffic effects probably persist for many years. In these cases, a considerably larger proportion of field area might well be compacted, so in this article the impact of CTF is compared with systems with 50%, 75% and 100% field area compacted.

These emission calculations also assume that all existing compaction has been removed when CTF systems are adopted, which might not always be the case. Within the present dataset, for instance, CTF had been in place for only 2 years on the rigid soil of the Swan Hill site, which produced the smallest random traffic impact factor in the southern region. A different mechanism might have been at work in the 2015/16 Toowoomba crop where the site was selected and set up in the farmer's absence, and crop development in that specific area was poor in an otherwise excellent crop. The farmer subsequently pointed out

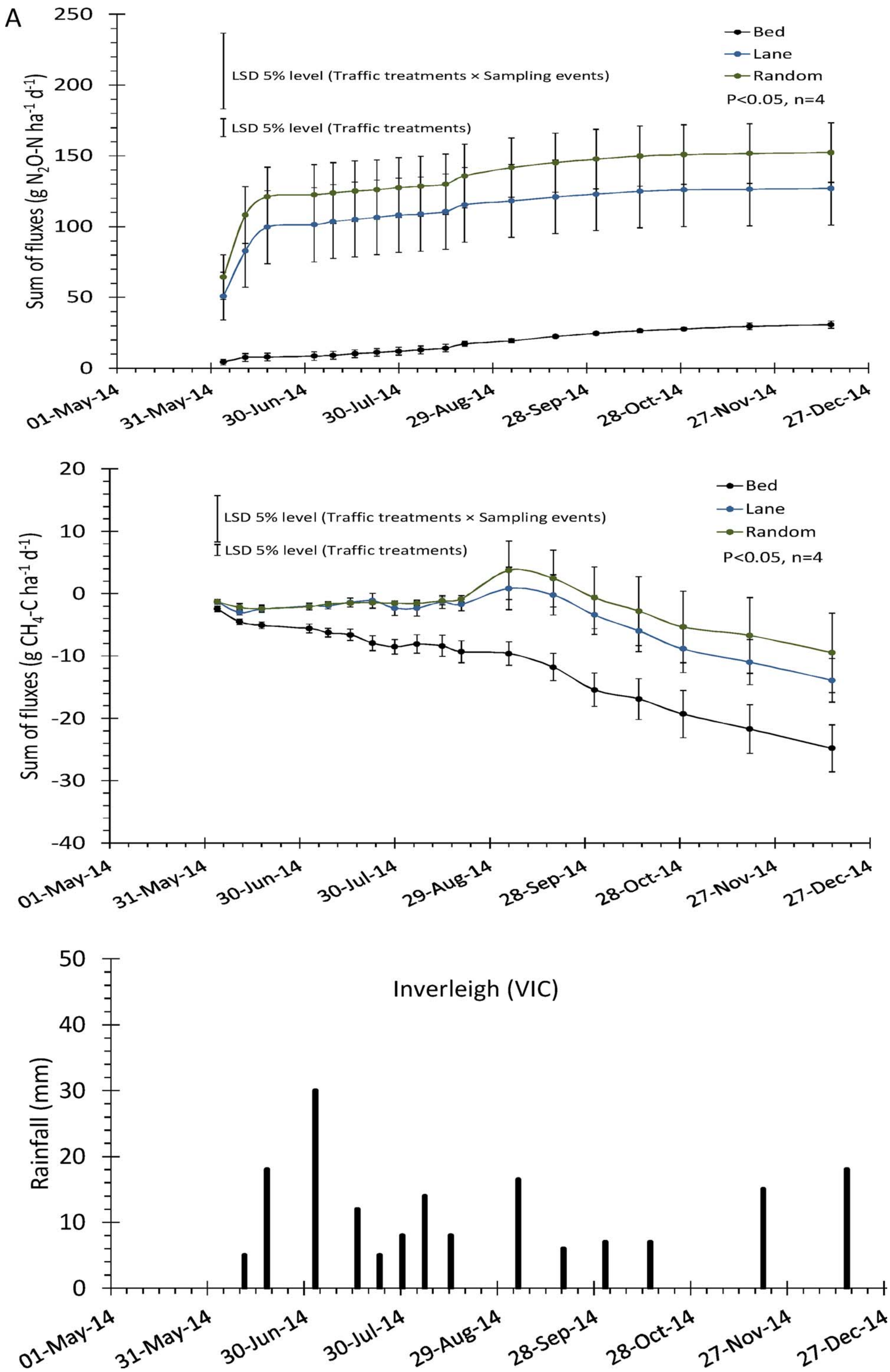

Fig. 2. A. Sum of nitrous oxide (N_2O) and methane (CH_4) fluxes, and rainfall in the sampling interval, respectively, recorded at the Inverleigh (Victoria) site during the 2014 winter wheat crop. Error bars on data points denote SD of means (n = 4). B. Sum of nitrous oxide (N_2O) and methane (CH_4) fluxes, and rainfall in the sampling interval, respectively, recorded at the Felton (Queensland) site during the 2013/2014 summer sorghum crop. Error bars on data points denote SD of means (n = 4).

that equipment manoeuvring had recently occurred in this area, which produced the lowest impact factor in the northern region. Large random treatment emissions at Esperance in both years and Inverleigh in 2014 appeared to be associated with high rainfall shortly after fertiliser applications

4.1. Nitrous oxide

Results of this work demonstrate a consistent increase in nitrous oxide (N_2O) emissions from trafficked soil across all sites and years, although mean N_2O emissions and traffic impact factors were greater in the southern region. Over all sites the mean traffic impact factors for N_2O emissions of random and traffic lane (TR and TL) soil were 2.28 and 1.88 respectively. These factors are substantially smaller than those found in potato production by Ruser et al. (1998) and Thomas et al. (2004), probably reflecting the smaller fertiliser inputs and soil moisture levels of rainfed broad acre wheat production. The largest N_2O traffic impact factor found in the present work was 4.97, for the 2014 Inverleigh (Victoria) wheat crop (Fig. 2A), where emissions would have been influenced by poultry manure distributed shortly before seeding (Thorman et al., 2006) and high rainfall shortly afterwards. The smallest random traffic impact factor (1.24) was found at Toowoomba

(Queensland) in the 2015/16 sorghum crop, a site subsequently found to be compromised by prior compaction, and another relatively small traffic impact factor was found at Swan Hill, the site where CTF had been in place for only 2 years on a rigid soil with no mechanical amelioration. Table 1 also shows instances where lane emissions were not much greater than those from beds, and there is no clear reasons for this. Fertiliser placement is one possible factor.

None of the conditions which might account for particularly high or low emissions would be unexpected in Australian grain production, so the mean N_2O traffic impact values noted above appeared to be a reasonable basis for calculating CTF effects on nitrous oxide emissions. Where CTF with 15% traffic lane area replaces non-CTF systems with 50%, 75% or 100% area random wheeled, Eq. (1) indicates that N_2O emissions from CTF would be 69%, 58% or 50% respectively of their previous values.

The Australian National Inventory Report (Anon., 2015), notes emission factors (EF's) of 0.85% and 0.05% for non-irrigated cropping in high and low rainfall areas respectively. Horsham and Swan Hill are low rainfall with less than 500 mm annually, but other sites are all close to 600 mm rainfall year. Applying a site-weighted EF of 0.64% to the overall mean N application rate of 82.8 kg ha^{-1}, indicates a mean loss of 0.53 kg N_2O-N would generally be expected in non-CTF grain production at these sites. The objective of this work was to demonstrate the relative effects of CTF systems, but it is interesting to compare this with the quantitative mean N_2O-N emission measurements from this work. Overall mean measured emissions (5.96, 4.67 and 2.76 g ha^{-1} d^{-1} for random, lane and CTF bed areas respectively) correspond to total emissions of 0.88, 0.69 and 0.41 kg N_2O-N per ha over the average monitoring period of 148 days. Eq. (1) indicates emissions from non-CTF cropping with 50% area random trafficked would be 0.64 kg N_2O-N ha^{-1}. Taking into account the issues of low sampling intensity and sampling bias this appears to be reasonably consistent with the expected value of 0.53 kg N_2O-N ha^{-1} derived from the National Inventory Report (Anon., 2015).

On this basis, when CTF replaces non-CTF systems with 50%, 75% or 100% area random wheeled, N_2O-N emissions should be reduced by 0.16, 0.22 or 0.26 kg N_2O-N ha^{-1} respectively. These quantities are small, but N_2O normally represents only a small proportion of total denitrification losses that are comprised of both N_2 and N_2O emissions. Studies from fertilised cropping systems have demonstrated that N_2 emissions usually exceed N_2O emissions by more than an order of magnitude (Rolston et al., 1978; Scheer et al., 2009). Recent research has also shown that soil compaction increases the ratio of N_2 to N_2O emitted (Harrison-Kirk et al., 2015), and N_2/N_2O ratio of up to 70 have been found in some situations (Scheer et al., 2015). A reduction in losses of 0.16 kg N_2O-N ha^{-1} from 50% random-trafficked soil might therefore indicate a soil N loss in the range 1.6–11.2 kg N ha^{-1}.

4.2. Methane

Data from all sites were consistent in demonstrating a negative sum of fluxes (i.e. uptake or absorption) of methane (CH_4) from all non-trafficked permanent crop beds, but the sum of fluxes from trafficked treatments varied from positive (emission) to negative (uptake). Fluxes from individual sites and treatments varied substantially (range: −5.2 to +1.4 g ha^{-1} d^{-1}, Table 1) but the CH_4-C uptake by non-trafficked CTF beds was always greater than that from random and permanent lane treatments. The mean difference between uptake of these treatments and CTF beds (1.81 and 1.85 g ha^{-1} d^{-1}, respectively) was similar, but mean differences were greater in the southern region.

Overall mean fluxes from random, lane and CTF bed were −0.29, −0.26 and −2.10 g CH_4 ha^{-1} d^{-1}, respectively, and individual CH_4 flux characteristics showed a tendency to reduced uptake after large rainfall events. This reduction might be expected when gas diffusion is retarded by soil compaction and high levels of soil moisture (Ball, 2013).

4.3. Environmental impact

Mean daily GWP emissions set out in Table 1 combine the effects of N_2O-N and CH_4-C in terms of CO2-e, and are the basis of GWP traffic impact factors for each site, which show that mean GWP values were generally larger in the southern region. Overall mean GWP values are approximately 6% greater than those from N_2O alone, illustrating the relatively small, but positive effects of CH_4 uptake on GWP emissions. Where CTF with 15% traffic lane area replaces non-CTF systems with 50%, 75% or 100% of field area random wheeled, Eq. (1) indicates that GWP emissions from CTF would be respectively 67%, 55% or 47% of their previous values.

Overall mean GWP emissions of (2.78, 2.18 and 1.22 kg CO2-e ha^{-1} d^{-1} for random, lane and CTF bed areas, respectively) correspond to total emissions of 409, 322 and 181 kg CO2-e ha^{-1} over the period of measurement. Using this data, Eq. (1) indicates that total emissions of 295 kg CO2-e ha^{-1} might be expected from non-CTF with 50% trafficked area. This appears to be reasonably consistent with the GWP equivalent (248 kg CO2-e ha^{-1}) of the 0.53 kg ha^{-1} average N emissions for these sites, derived from the National Inventory Report (Anon., 2015). With due regard to the uncertainties resulting from low-intensity sampling, this data indicates that when CTF replaces non-CTF systems with 50%, 75% or 100% area random wheeled, GWP emissions should be reduced to 72%, 61% or 52% respectively of their previous values.

Additional GWP effects might be expected from the reduction in fuel requirement of cropping operations demonstrated by Tullberg (2000) and Luhaib et al. (2017), and noted in many anecdotal reports by graingrowers. Similarly, in addition to the reduced denitrification loss demonstrated here, improved soil structure (McHugh et al., 2009) and increased infiltration rates under CTF (Tullberg et al., 2001) have been shown to reduce fertiliser N loss in run-off (Rohde et al., 2012) and off-site emissions. The combination of these effects might be expected to have a useful cumulative impact on the life-cycle GWP of Australian grain production.

5. Conclusions

Mean results from low-intensity N_2O and CH_4 emission monitoring in 15 crops in the extensive dryland grain growing areas of Queensland, Victoria and Western Australia have demonstrated that:

1. Nitrous oxide emissions from random-trafficked soil are greater than those of neighbouring non-trafficked soil by an average factor of > 2. Non-trafficked soil in these systems also absorb approximately 1.8 g ha^{-1} d^{-1} more methane than trafficked soil.
2. Controlled traffic farming reduces the proportion of field area affected by traffic, and might be expected to reduce the GWP of soil emissions of N_2O and CH_4 by 30%–50%.
3. Low-intensity monitoring is the basis for a first estimate of the quantitative impact of controlled traffic farming: a reduction in annual emissions from dryland grain farming by 90–150 kg ha^{-1} CO_2-e. If these estimates are correct, converting 50% of the 22 M ha of dryland grains in Australia to CTF could reduce annual emissions from Australian cropping (currently 5.0 Mt CO_2-e, Anon., 2015) by 0.6–1.7 Mt CO_2-e.
4. Emission effects of CTF are likely to be much greater in irrigated production (e.g., cane, cotton, and horticulture) where N fertiliser inputs and soil moisture levels due to irrigation are greater and more frequent traffic accompanies the more intensive management.
5. Further work is required to:
   a) Refine and confirm the quantitative impact of CTF using high-intensity sampling accompanied by thorough monitoring of soil and environmental factors.
   b) Adjust and validate soil/plant models (e.g. APSIM, Keating et al., 2003) to generalise and expand our understanding of traffic impact on N_2O emissions and denitrification losses in parallel

with c) and d) below.

c) Assess the emission impact of less heavily loaded field traffic (e.g. implement frame wheels running on permanent crop beds), and improved N fertiliser placement.

d) Demonstrate and assess field traffic impacts on soil emissions from other cropping systems, particularly those of intensive agriculture, and the steps necessary to control traffic in these industries.

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