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Recommendations for country-specific EF_1 values for farm dairy effluent (FDE) and urea fertiliser - Final Report

MPI [Agreement Number 16801)

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Recommendations for country-specific EF_1 values for farm dairy effluent (FDE) and urea fertiliser – Draft Final Report

MPI (Agreement Number 16801)

July 2015

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1. Executive Summary

This report presents recommendations for country-specific EF_1 values for farm dairy effluent (FDE) and urea fertiliser. These recommendations are based on research conducted across New Zealand to quantify EF_1 (% of applied N lost as N_2O-N) under contrasting soil and climatic conditions. The research programme was funded by the Ministry for Primary Industries (MPI) under agreement 16801. The objectives of this study were to: (1) determine, in four regions, EF_1 for FDE applied to pastures with and without a history of receiving FDE, and (2) conduct a meta-analysis of EF_1 using FDE data from the current study, an earlier MPI/Ballance Agri-Nutrient funded study (van der Weerden et al. 2014) and FDE- and urea fertiliser-EF_1 data from previous NZ studies to determine country-specific EF_1 values.

Objective 1: Determine EF_1 for FDE applied to pastures with and without a history of receiving FDE.

- Field experiments were conducted in four regions (Waikato, Manawatu, Canterbury and Otago) where farm dairy effluent (FDE) was applied at *ca* 50 kg N/ha to dairy pastoral soils that had either received applications of FDE for at least 10 years or had never received FDE.
- FDE was applied in spring 2014 to determine N_2O emissions and corresponding EF_1 values.
- Effluent irrigation history had a significant effect ($P < 0.01$) on cumulative N_2O losses measured in Otago; however there was no significant effect of effluent history in all other regions ($P > 0.05$).
- Effluent history had no effect on FDE EF_1 in all regions ($P > 0.05$).
- The arithmetic mean FDE EF_1 value was 0.34% ± 0.12% (mean ± SEM, n=8).

Objective 2: Determine country specific EF_1 values for FDE and urea fertiliser by conducting a meta-analysis of relevant data.

- The results from the four regional experiments in objective 1 were combined with results from 20 other regional FDE trials and 26 regional urea fertiliser trials to provide a total of 50 data points for a meta-analysis to determine EF_1 for urea and FDE.
- All data were produced from field trials conducted in Waikato, Manawatu, Canterbury and Otago from 2003 to 2015.

- There were 26 trials conducted in Waikato, 10 in Manawatu, 6 in Canterbury and 8 in Otago.
- Free draining soils were used for 33 trials, with the remaining 17 trials conducted on poorly drained soils.
- Most trials were conducted in spring (25), followed by winter (14), autumn (7) and summer (4).
- The overall mean EF_1 value for the combined FDE and urea fertiliser data was calculated as 0.48%, with a lower and upper 95% confidence interval of 0.00% and 1.32%.
- There was no significant difference in the mean EF_1 values for FDE and urea ($P > 0.05$), which were respectively calculated from the combined data as 0.26% (0.00% – 1.12%) and 0.59% (0.00% – 1.48%) (ranges represent lower and upper 95% confidence intervals).

Recommendations

- That separate single-country EF_1 values are used for FDE and urea fertiliser, due to the difference in characteristics of the two N sources. Urea is a readily available source of N while FDE contains both organic N and readily available ammoniacal-N.
- That MPI adopt an EF_1 value of 0.3% for FDE and 0.6% for urea fertiliser in future New Zealand agricultural greenhouse gas inventories.

2. Introduction

Application of farm dairy effluent (FDE) to agricultural soil provides a nitrogen (N) source for nitrous oxide (N_2O) production and emissions via nitrification and denitrification processes. The New Zealand agricultural greenhouse gas inventory currently uses the IPCC EF_1 (emission factor, % of applied N emitted as N_2O) default value of 1% for FDE application to land (Ministry for the Environment, 2014). However, research would suggest that N_2O emissions are considerably lower than 1% of applied N (van der Weerden et al. 2014). In a recently completed project, funded by MPI and Ballance Agri-Nutrients, van der Weerden et al. (2014) conducted four trials across the country and calculated a mean EF_1 value of 0.27% ± 0.17% (mean ± SEM, n=4). When combined with 6 values from 2 previous New Zealand studies (Bhandral et al. 2007; Li et al. 2014), the mean EF_1 was similar although the level of variation was reduced (0.30% ± 0.10: mean ± SEM; n=10).

While there has been a recent increase in the number of EF_1 values reported for FDE application, none of these field trials were conducted on paddocks with a history of effluent application. It is possible that a history of effluent application influences the magnitude of N_2O production due to the addition of organic manure over time elevating soil C content. This may lead to greater background emissions, and emissions following FDE application from effluent-irrigated pastoral soils, than from pastoral soils with no effluent irrigation history. Furthermore, apart from available C influencing substrate supply for denitrifiers, it is also possible that nitrifying and denitrifying microbial activity may be influenced by the repeated application of effluent over several years.

The objectives of this study were to provide recommendations on country-specific EF_1 values for FDE and urea fertiliser by (1) extending the existing EF_1 FDE dataset with additional measurements, and (2) conducting a meta-analysis of FDE and urea fertiliser EF_1 values using all available New Zealand data.

3. Materials and methods

3.1 Field experiment

3.1.1 Site and soil description

Field experiments were initiated in 4 regions (Waikato, Manawatu, Canterbury and Otago) of New Zealand in September 2014 where fresh FDE was applied to dairy farm paddocks with no history of receiving effluent ('no FDE history') or to paddocks with a history of receiving effluent ('FDE history'). Soils were selected to provide representative soil drainage classes, with well-drained soils being used in Waikato, Manawatu and Canterbury while a poorly-drained soil was used in Otago. These four regions represent major dairying regions of NZ and also provide variation both in climates and soils for use in this study to determine cumulative N_2O emissions and EF_1 values for FDE. All the regions have temperate climates, with 1,240 mm annual rainfall and mean annual temperature of 14°C in Waikato; 970 mm and 13°C in Manawatu; 680 mm and 11.5°C in Canterbury; and 700 mm and 9°C in Otago. Table 1 details soil properties at each site. All of the sites support a grazed, predominantly ryegrass (*Lolium perenne*)/white clover (*Trifolium repens*) pasture. Animals were excluded from the experimental sites for at least two months prior to treatment application. We ensured paddocks for the 'FDE history' treatment had received FDE for at least 10 years. Based on farmer information, effluent had been applied for the past 20, ~25, 14 and 10 years to the paddocks used at the Waikato, Manawatu, Canterbury and Otago sites, respectively. Effluent application was excluded from experimental sites for at least 6 months prior to treatment application.

3.1.2 Treatments

Experimental treatments were fresh FDE applied to paddocks with or without a history of receiving FDE. Fresh FDE was collected either on the day of application or one day earlier from the sump of dairy milking shed yards on local dairy farms within each region to represent typical fresh FDE applied to pasture under spring conditions. Each experimental site included 12 plots to accommodate two treatments, FDE and a non-treated control (C), applied in a randomised block design (6 reps per treatment). Each plot had an area of 1 m × 2 m, where a chamber base was inserted to a depth of approximately 100 mm in the middle of a 1 m x 1 m area while the adjacent area of 1 m x 1 m was used for destructive soil sampling.

Table 1. Details of drainage class, soil type, paddock effluent history (including years receiving effluent), location and treatments within each region.

Region	Soil type	Soil Order	Paddock effluent history	GPS coordinates	Treat-ment	Soil properties (0 - 7.5 cm)						
						Olsen P (µg ml^{-1})	pH	Organic C (%)	TKN (%)	Bulk density (g cm^{-3})	Particle density (g cm^{-3})	Total porosity (cm^3 cm^{-3})
Waikato	Horotiu silt loam	Typic Orthic Allophanic	no FDE history	37º 42' 04. S 175º 14' 11. E	Control FDE	97	6.1	6.7	0.67	0.85	2.32	63
			FDE history (20)	37º 42' 02. S 175º 14' 06. E	Control FDE	114	6.4	7.2	0.73	0.83	2.31	64
Manawatu	Recent sandy[A]	Typic Fluvial Recent	no FDE history	40º 10' 18. S 175º, 48' 42. E	Control FDE	53	6.9	1.4	0.14	1.26	2.66	52
			FDE history (20-30)	40º 10' 09. S 175º, 48' 53. E	Control FDE	57	5.9	2.5	0.26	1.16	2.61	55
Canterbury	Templeton fine sandy loam/silt loam.	Immature Pallic	no FDE history	43º 38' 18. S 172º, 26' 34. E	Control FDE	26	5.8	3.7	0.35	1.12	2.56	56
			FDE history (14)	43º 38' 18. S 172º, 26' 34. E	Control FDE	20	6.0	3.7	0.33	1.06	2.58	59
Otago	Koau deep silty clay loam	Acidic Orthic Gley	no FDE history	45º 56' 17. S 170º 10' 59 E	Control FDE	21	6.2	9.3	0.83	0.75	2.44	69
			FDE history (10)	45º 56' 27. S 170º 11' 05. E	Control FDE	65	6.5	10.8	0.99	0.73	2.39	69

[A] the 'no FDE history' site was classified as a sandy loam, whilst the 'FDE history' site was classified as a loamy silt

Table 2: Chemical characterisation of FDE.

Region	Total Solids (%)	pH	Total C concen-tration (g/L)	Total N concen-tration (g/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	TAN (% of total N)
Waikato	0.7	8.0	2.3	0.54	229	<5	42
Manawatu	2.1	7.5	1.8	0.28	169	<5	60
Canterbury	0.3	8.3	0.9	0.43	210	<5	49
Otago	0.8	7.4	2.2	0.46	285	<5	62

On application day, FDE was applied to a depth of 10 mm to the chamber base internal areas (between 0.05 m^2 and 0.07 m^2, varying between the regions) and to the adjacent soil sampling plots (1 m × 1 m). An FDE subsample was collected in duplicate for chemical analysis to characterise the FDE. FDE total N concentrations varied from 0.28 to 0.54 g/L, leading to total N loading ranged from 28 to 54 kg N/ha. FDE total solids (TS) ranged from 0.3% to 2.1%, while pH ranged from 7.4 to 8.3 (Table 2). Carbon content of the FDE ranged from 0.9 to 2.50 g C/L. The total ammoniacal-N content (TAN) of the FDE ranged from 169 to 285 mg N/L, with TAN representing 42-62% of the total N. Pasture growth was managed by cutting herbage when the pasture was about 120 mm height to approximately 30-50 mm height (or about 1400 kg DM/ha) in the study areas.

3.1.3 N_2O emissions and EF_1 calculation

Nitrous oxide emissions were measured using a static chamber technique (de Klein et al. 2014). Measurements were taken twice a week for the first 6 weeks after treatment application and then once a week, with extra samplings conducted when rainfall exceeded 10 mm in 24 hours. On each sampling day, N_2O measurements were carried out once between 10 a.m. and 12 p.m. standard time (van der Weerden et al. 2013). Headspace gas samples were taken during a cover period of 40 minutes at times t_0, t_{20} and t_{40} for the first 13 gas sampling occasions and during a cover period of 40 minutes at times t_0 and t_{40} for the remainder of the sampling occasions. On each sampling day at each site, 2 background atmosphere samples were taken. Gas samples were analysed by gas chromatography, with samples collected in Waikato, Canterbury and Otago analysed at Lincoln University, Canterbury, while samples collected from Manawatu were analysed by Landcare Research, Palmerston North. Gas and soil sampling was carried out over a 3-4 month period, until N_2O emissions and soil mineral N content had returned to background levels (as measured from the control treatment). In our earlier study (van der Weerden et al. 2014), emissions were measured over a 12 month period. Data from that study suggested N_2O emissions were complete after 3-4 months following FDE application at ~50 kg N/ha.

The hourly N_2O fluxes (mg N m^{-2} h^{-1}) were calculated from the increase in head space N_2O over the sampling time (de Klein et al. 2014).

$$N_2O\,flux \quad = \quad \frac{\delta N_2O}{\delta T} * \frac{M}{Vm} * \frac{V}{A} \qquad (1)$$

where, δN_2O is the increase in head space N_2O over time (µL/L); δT is the enclosure period (hours); M is the molar weight of N in N_2O; Vm is the molar volume of gas at the sampling temperature (L/mol); V is the headspace volume (m^3); and A is the area covered (m^2).

These hourly emissions were integrated over time, for each chamber, to estimate the total emission over the measurement period. The N_2O emission factors (EF_1, N_2O-N emitted as a % of N applied) were then calculated by dividing the treatment-induced emission by the amount of N applied for each treatment (de Klein et al. 2014):

$$EF_1 \quad = \quad \frac{Total\ FDE\ N_2O \quad - \quad Total\ Control\ \ N_2O}{FDE\ N\ applied} \quad \times \quad 100\% \qquad (2)$$

where EF_1 is emission factor (N_2O-N emitted as a % of N applied), Total FDE N_2O and Total Control N_2O are the cumulative N_2O emissions from the FDE and control plots, respectively (kg N ha^{-1}), and FDE N applied is the rate of N applied (kg N ha^{-1}).

3.1.4 Soil sampling

Soil bulk density measurements were taken at the start of the experiment. Briefly, stainless steel rings (100 mm diameter x 75 mm height; internal volume = 605 cm^3) were inserted into the soil surface layer (0-75 mm) to collect intact soil cores. The soil surface of the intact core was flush with the top of the ring and after careful extraction from the soil the bottom of the core was trimmed to be flush with the bottom of the ring. The soil cores were retained in their collection rings and dried at 105 °C for 48 hours and then dry soil recorded and bulk densities calculated (g cm^{-3}).

On each gas sampling day, soil samples (75 mm deep, 25 mm diameter) were taken from all plots for determination of soil nitrate (NO_3^-), ammonium (NH_4^+) and water content. However, during the first 6 weeks when samples were collected twice a week, soil mineral N determination was limited to once a week. In the laboratory on the same or the following day, the soil samples were thoroughly mixed and about 15 g fresh soil (about 10 g dry soil equivalent) extracted for 1 hour in 50 mL 2 *M* KCl. The filtered solution was then frozen until analysed for nitrate N (plus nitrite N), and ammonium N. The remainder of the mixed soil was dried at 105 °C for 24 hours, to determine gravimetric soil water content. Volumetric water content was calculated by multiplying gravimetric water content by bulk density (Luo et al., 2007). Water-filled pore space (WFPS) was calculated by dividing volumetric water content by total porosity (Linn and Doran, 1984). Total porosity was determined from measured bulk density and measured particle density. Particle density was measured by evacuating soil and water in pycnometers and referencing with the density of water (Gradwell, 1972).
Daily rainfall, ambient air and soil temperatures (50 mm depth) were logged for the entire experimental period at a site near to the experimental site in each region. A manual rain gauge was installed at each site to determine total rainfall between sampling days.

3.1.5 Statistical analysis

An analysis of variance (ANOVA) was performed to determine if the cumulative N_2O emission and EF_1 data obtained from paddocks with or without a history of FDE application were significantly different. Cumulative N_2O emission and EF_1 data, across all regions and sites, were found to be non-normally distributed and thus violated the assumptions for analysis of variance. Therefore, cumulative N_2O emission values were log (x) transformed prior to analysis using Genstat (version 13; Payne et al. 2010). EF_1 data were log (x+a) transformed prior to analysis, where *a* values were estimated by optimising for normality. The term *a* was added due to the presence of negative values. A single outlier was omitted from the Otago cumulative emissions data, while a single outlier was also omitted from the Canterbury EF_1 data: in both cases the emissions from the FDE treatment were considerably lower than from the corresponding control. The reported cumulative means and EF_1 values were obtained following back-transformation. Prior to back-transformation, Manawatu and Canterbury cumulative means have been adjusted for covariates using flux data measured prior to treatment application. Adjusting cumulative flux in accordance with pre-treatment fluxes was considered an appropriate step as it reduced the standard error of the difference (SED). Other regions did not require adjustment for covariates.

3.2 Meta-analysis

Meta-analysis is a quantitative synthesis of results across multiple studies (Kelliher et al. 2011). A meta-analysis on EF_1 values was conducted on FDE data from the current study and from previous FDE studies, in addition to published and unpublished urea fertiliser data. In total, 50 EF_1 values from 46 field trials were included in the meta-analysis, where some trials included both N sources (urea fertiliser and FDE; van der Weerden et al. 2014). All field sites were classified according to 2 drainage classes (free versus poor), region and season. Free draining soils were used for 33 studies, with the remaining 17 studies conducted on poorly drained soils. Trials were conducted from 2003 to 2015. The 50 EF_1 values were derived from four regions: Waikato (26), Manawatu (10), Canterbury (6) and Otago (8). Season for each trial was defined by determining which month the trial's 15th day occurred as follows: January, February and December for summer, March, April and May for autumn, June, July and August for winter and September, October and November for spring, thereby following the same approach as Kelliher et al. (2014). Most trials were conducted in spring (25), followed by winter (14), autumn (7) and summer (4).

To determine the best model to describe the data, we tested the significance of effects using rank transformed data; the significant effects were region and N source x season. For estimation purposes, we used a natural log transformation with N source included as a fixed effect and other effects fitted as random effects. The estimated effects were back-transformed and bias corrected. The bias correction was done by scaling the back-transformed estimates by the amount required to get their weighted mean to be the same as the overall mean of the EF_1 value (Kelliher et al. 2014).

4. Results

4.1 Field experiment

4.1.1 Soil and climatic conditions

Soil temperatures were similar at the Waikato and Manawatu sites, averaging 15.2 °C at 5cm depth during the first month of the study. Soil temperature increased over the course of the study (Fig. 1c and 3c), resulting in a 3-month average of 17.6 °C across the sites used in the North Island. Soil temperatures were also similar at the two South Island sites (Canterbury and Otago; Fig. 5c and 7c), averaging 12.5 °C at 5cm depth during the first month of the study and 15.1 °C over the first three months.

The Canterbury site received the largest amount of rainfall, with 388 mm being recorded over a 126 day period. Rainfall in Waikato, Manawatu and Otago over the study period was lower, at 288, 182 and 143 mm recorded over trial periods of 105, 106 and 102 days, respectively. It should be noted that N_2O measurements were made for 20-23 more days in Canterbury compared to the other regions due to differences in N_2O fluxes and soil mineral N between the FDE and control treatments being observed for a longer period. Measurements were stopped once there was no difference in N_2O fluxes and soil mineral N between the FDE and control treatments. When comparing regional rainfall over the first three months of the measurement period, Waikato and Canterbury had similar rainfall totals (279 and 284 mm, respectively), while the Manawatu and Otago sites received 181 and 126 mm, respectively.

The WFPS data presented in Figures 1c, 3c, 5c and 7c and described below refer to the FDE plots, as this treatment is of primary interest with respect to N_2O emissions (as opposed to control plots). Soils at the Waikato sites were relatively moist during the first month of the trial, with WFPS averaging 85 and 80% at the 'no FDE history' and 'FDE history' sites, respectively (Fig. 1c). Soil moisture content decreased slightly over the following two months, with WFPS averaging 76 and 70%, respectively, over the 3 months following FDE application. Regular rainfall at the Manawatu sites maintained soil water content at between 55 and 75% WFPS during the first 2 months (Fig. 3c). This was followed by a month of dry weather, resulting in WFPS declining to a very low level of 9%, averaged across the two sites. The 'no FDE history' site consistently maintained a slightly lower WFPS compared to the 'FDE history' site, averaging 61 and 66%, respectively, over the first month, and 53 and 59%, respectively, over the 3 months following treatment application.

There was little difference in WFPS between the 'no FDE history' and 'FDE history' sites in Canterbury, with soil water content averaging 61% across both sites in the first month (Fig. 5c). Soil water content remained relatively constant for the entire trial due to regular rainfall, averaging 64% over the 3 months following treatment application. In Otago, soil water content was greater than in other regions (Fig. 7c). The 'no FDE history' site maintained a slightly lower WFPS compared to the 'FDE history' site, with average water contents of 92 and 98%, respectively, during the first month of the trial. Rainfall eased off during the final month of the trial, leading to a decline in WFPS to ~40% by late January. The average WFPS over the first 3 months of the trial averaged 75 and 80% WFPS for the 'no FDE history' and 'FDE history' sites, respectively.

The FDE treatments applied in Waikato elevated soil NH_4-N content to 10-12 mg N/kg dry soil one day following application (Fig. 2a). Thereafter, soil NH_4-N content declined to levels measured in adjacent control treatments. The 'no FDE history' site maintained slightly higher soil NH_4-N contents in both control and FDE treatments compared to the 'FDE history' site. In Manawatu, Canterbury and Otago, soil NH_4-N content remained relatively unchanged following FDE application onto both 'no FDE history' and 'FDE history' sites, with concentrations never exceeding 8 mg N/kg dry soil (Fig. 4a, 6a & 8a).

Initial soil NO_3-N content increased to *ca* 33 mg N/kg dry soil following application of the FDE treatment to the 'FDE history' site in Waikato (Fig. 2b). A smaller increase in soil NO_3-N was observed for the 'no FDE history' site in this region. Thereafter, soil NO_3-N contents declined to about *ca* 5 mg N/kg dry soil in all treatments and controls by the end of November. However, soil NO_3-N contents increased in all treatments (including controls) in December and January and the increases were greater at the 'FDE history' site compared to the 'no FDE history' site. The increased soil NO_3-N contents measured both in December and January were probably due to heavy rainfall after relatively dry periods (Fig. 1c). The dry-wet cycle can lead to high levels of mineral N, which may have over-ridden any paddock history of FDE treatment effects. Despite the increased levels of NO_3-N, there were no significant differences in NO_3-N contents between the FDE treatment and control either at the 'no FDE history' or 'FDE history' sites during these measurement months. In Manawatu, soil NO_3-N content remained below 8 mg N/kg dry soil throughout the entire trial for all treatments at both sites (Fig. 4b). Soil NO_3-N content increased to between 11-14 mg N/kg dry soil following FDE application in Canterbury and Otago; thereafter soil NO_3 levels remained relatively low (Fig. 6b & 8b).

4.1.2 Nitrous oxide emissions

Hourly fluxes

Hourly N_2O fluxes from the control treatments in Waikato reached 0.22-0.27 mg N_2O-N/m^2/hr in the first week of the trial (equivalent to 58-65 g N_2O-N/ha/d when multiplying mg N_2O-N/m^2/hr by 240), after which fluxes remained low until towards the end of the experiment when there was a small increase to ~0.14 mg N_2O-N/m^2/hr following a significant rainfall event (48 mm in 1 day; Fig. 1). In Manawatu, Canterbury and Otago,

N_2O fluxes from the control treatments generally remained low (< 0.1 mg N_2O-N/m^2/hr) throughout the experiments (Figs. 3a, 3b, 5a, 5b, 7a and 7b).

Hourly N_2O fluxes from the FDE treatments peaked within 1 day of application at most sites, with the largest fluxes measured from the 'no FDE history' site in the Waikato and the 'FDE history' site in Otago, both reaching 0.40 mg N_2O-N/m^2/hr (Figs. 1a and 7b). The Waikato 'FDE history' site also produced a relatively large peak flux of 0.28 mg N_2O-N/m^2/hr following FDE application (Fig. 1b), while the 'FDE history' site in the Manawatu and the 'no FDE history' site in Canterbury producing peak fluxes of 0.18 and 0.13 mg N_2O-N/m^2/hr 6 days and 1 day following FDE application, respectively (Fig. 3b and 5a). Apart from the peak fluxes measured soon after FDE application, N_2O fluxes remained relatively small. Indeed, fluxes from the FDE treatment were low (< 0.10 mg N_2O-N/m^2/hr) for the entire experiment at three of the sites (Manawatu 'no FDE history', Canterbury 'FDE history' and Otago 'no FDE history'; Figs. 3a, 5b and 7a).

Cumulative emissions

Cumulative N_2O emissions from FDE application were greatest in Waikato and Canterbury, with losses of between 1065 and 1377 g N_2O-N/ha being recorded over a 3-4 month period until fluxes and soil mineral N content returned to background levels (Table 3). Control treatments also produced relatively high cumulative losses, albeit always less than from the FDE treatment, ranging from 906 to 1130 g N/ha in these two regions. Cumulative losses from the Manawatu sites were lower, ranging from 499 to 814 g N/ha. In the Waikato, Manawatu and Canterbury, there was no significant difference in cumulative losses between the control and FDE treatments, nor between the 'no FDE history' and 'FDE history' sites ($P > 0.05$).

In contrast, cumulative losses in Otago were significantly greater from the FDE treatment compared to the control ($P < 0.01$; Table 3). Furthermore, the paddock's effluent history also had a significant effect on cumulative losses, with greater losses measured from the 'FDE history' site compared to those measured at the 'no FDE history' site ($P > 0.01$; Table 3). It should be noted, however, that these results are based on a single large flux measured at both the 'no FDE history' and 'FDE history' sites 1 day following FDE application (Fig.7a and 7b). Cumulative losses from FDE application ranged from 142 to 496 g N/ha, while the control treatments produced between 64 and 105 g N/ha.

Table 3: Cumulative N_2O emissions (g N_2O-N/ha) over a 3-4 month measurement period from FDE, applied to pasture with no FDE history or with a history of FDE application. Emissions are back-transformed and bias-corrected means of the transformation $\log_e (x+a)$, with 95% confidence intervals in brackets.

N treatment	Waikato	Manawatu	Canterbury	Otago
No FDE history				
Control	1019 (795 - 1305)	499 (345 - 657)	906 (675 - 1127)	64 (44 - 94)
FDE	1146 (894 - 1468)	500 (345 - 658)	1065 (794 - 1325)	142 (97 - 207)
FDE history				
Control	958 (748 - 1228)	578 (399 - 760)	1130 (842 - 1405)	105 (72 - 154)
FDE	1082 (844 - 1386)	814 (562 - 1071)	1377 (1027 - 1713)	496 (339 - 726)
P value[A]				
FDE vs control	NS	NS	NS	**
No FDE history vs FDE history	NS	NS	NS	**

[A] NS not significant; **: $p<0.01$

EF_1

Nitrous oxide emissions from FDE were measured over a 3-4 month period, with resulting EF_1 values ranging from 0.04 to 0.94%. All regions showed that there was no significant difference in EF1 between ‘no FDE history’ and ‘FDE history’ paddocks (Table 4).

Table 4: EF_1 values (%) for FDE applied to pasture with no FDE history or with a history of FDE application. EF_1 values are back-transformed and bias-corrected means of the transformation $\log_e(x+a)$, with 95% confidence intervals in brackets.

N treatment	Waikato	Manawatu	Canterbury	Otago
Farm dairy effluent				
Non-irrigated history	0.28 (-0.39 – 1.22)	0.20 (-0.76 - 1.67)	0.06 (-0.33 - 0.53)	0.29 (-0.01 - 0.96)
Irrigated history	0.04 (-0.56 – 0.88)	0.94 (-0.28 - 2.82)	0.12 (-0.28 – 0.61)	0.75 (0.20 – 2.00)
P value [A] (0.05) Non-irrigated vs Irrigated	NS	NS	NS	NS

[A] : NS = not significant

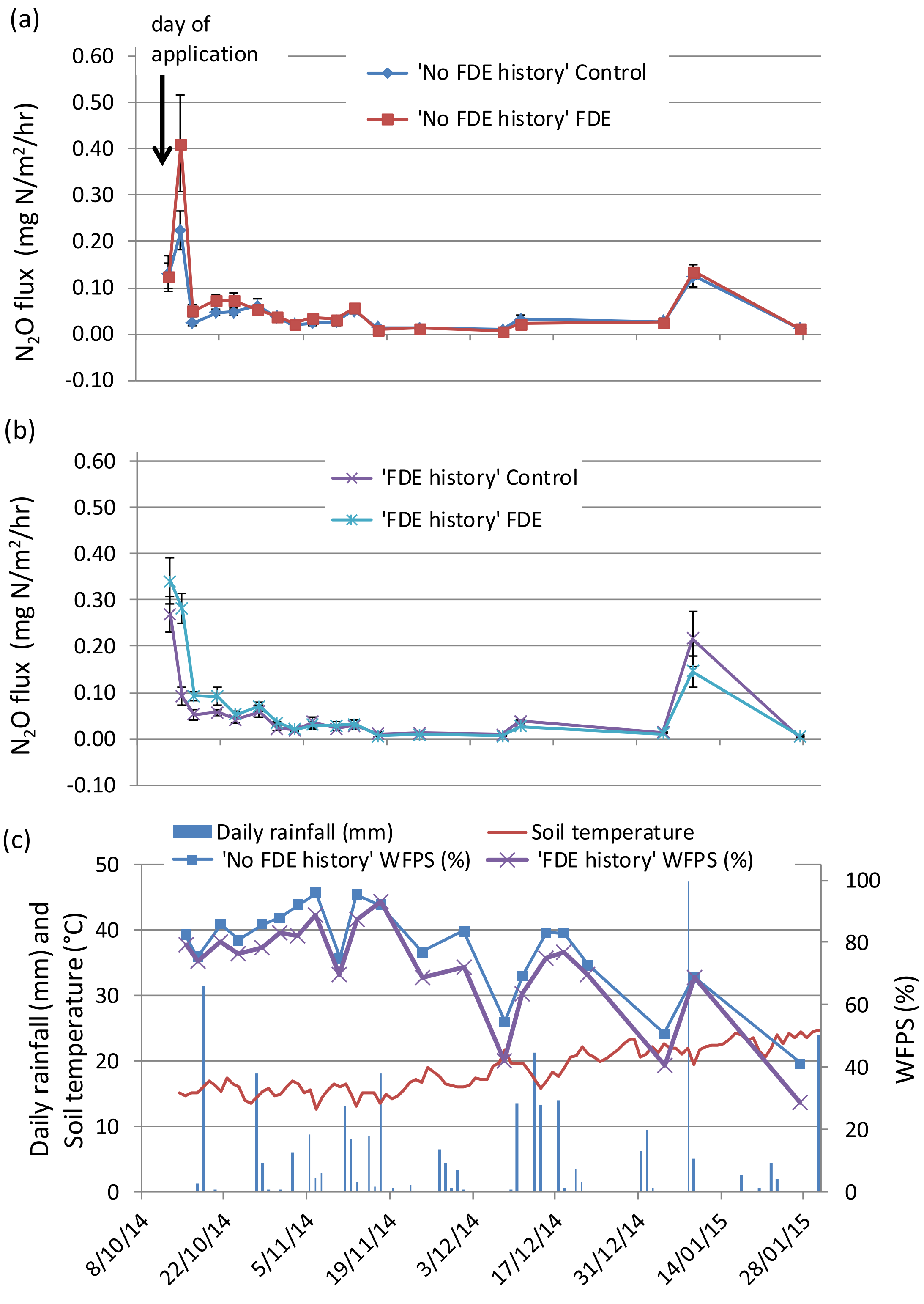

Figure 1. Waikato site (a): N_2O flux (mg N/m^2/hr) from effluent applied to pasture with **(a)** no FDE history and **(b)** FDE history; errors bar indicate ± SEM. **(c)**: Daily rainfall (mm), soil temperature (°C; 5cm depth) and WFPS (%; 0-7.5cm).

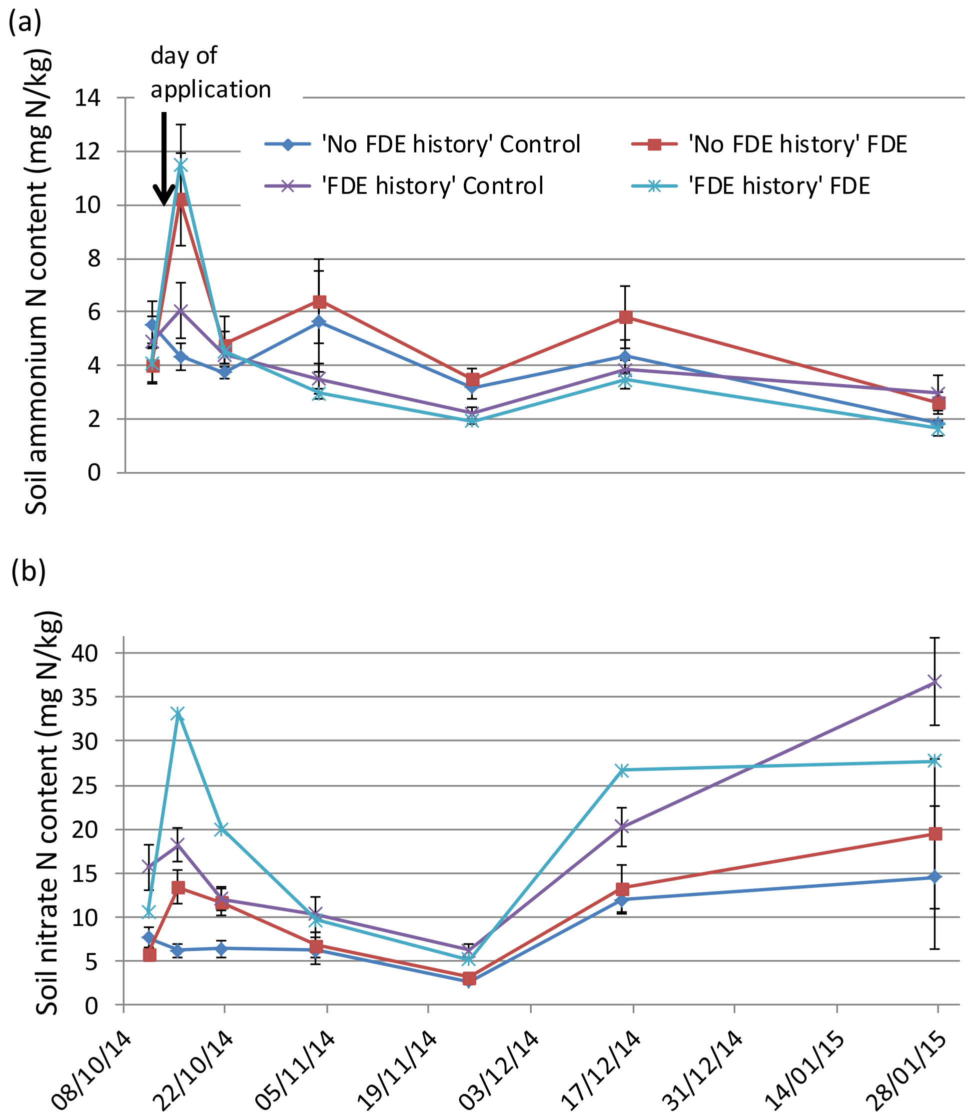

Figure 2. Waikato site (a): Soil ammonium-N and **(b)** nitrate-N contents (mg N/kg; 0-7.5cm depth) measured at the 'no FDE history' and 'FDE history' sites.

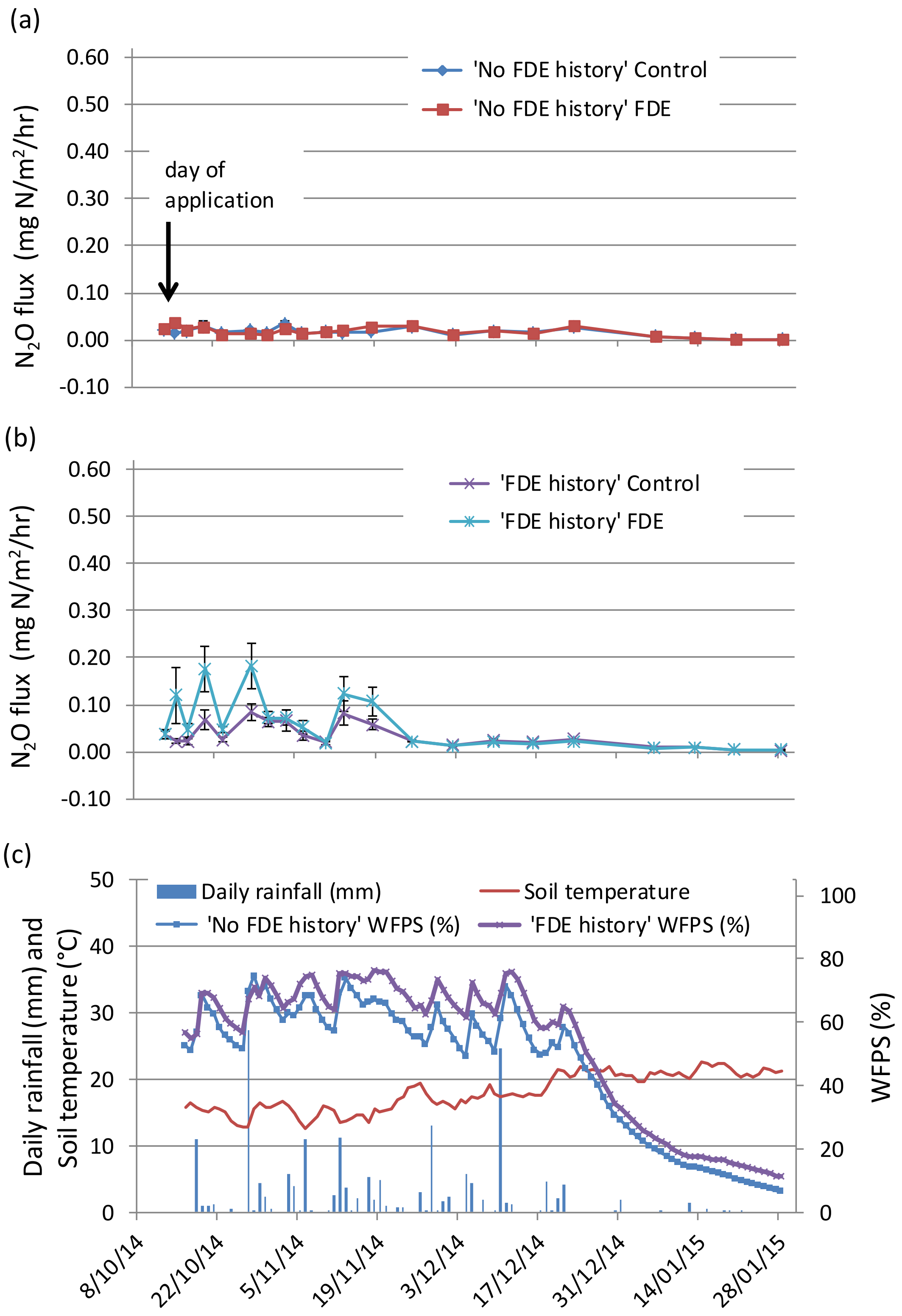

Figure 3. Manawatu site (a): N_2O flux (mg N/m^2/hr) from effluent applied to pasture with **(a)** no FDE history and **(b)** FDE history; errors bar indicate ± SEM. **(c)**: Daily rainfall (mm), soil temperature (°C; 5cm depth) and WFPS (%; 0-7.5cm).

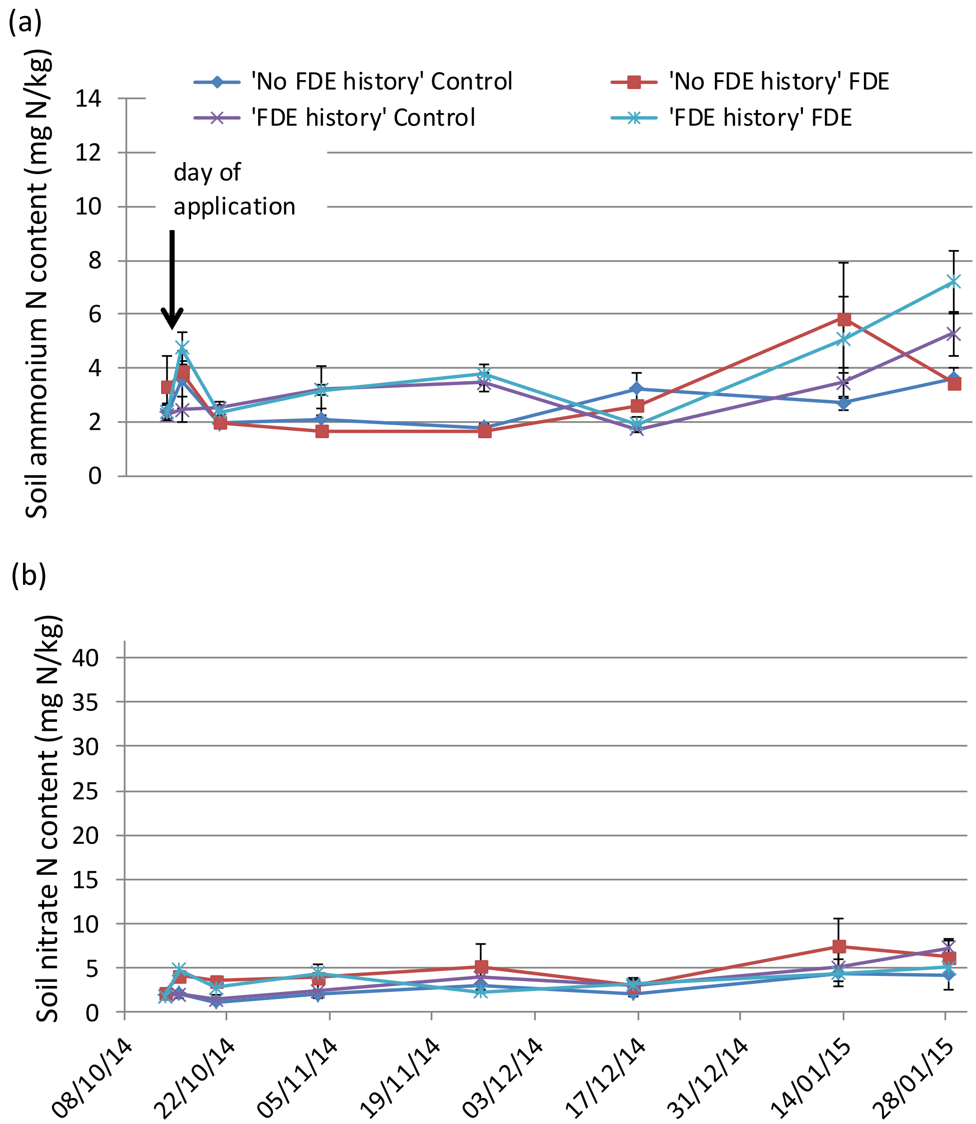

Figure 4. Manawatu site (a): Soil ammonium-N and **(b)** nitrate-N contents (mg N/kg; 0-7.5cm depth) measured at the 'no FDE history' and 'FDE history' sites.

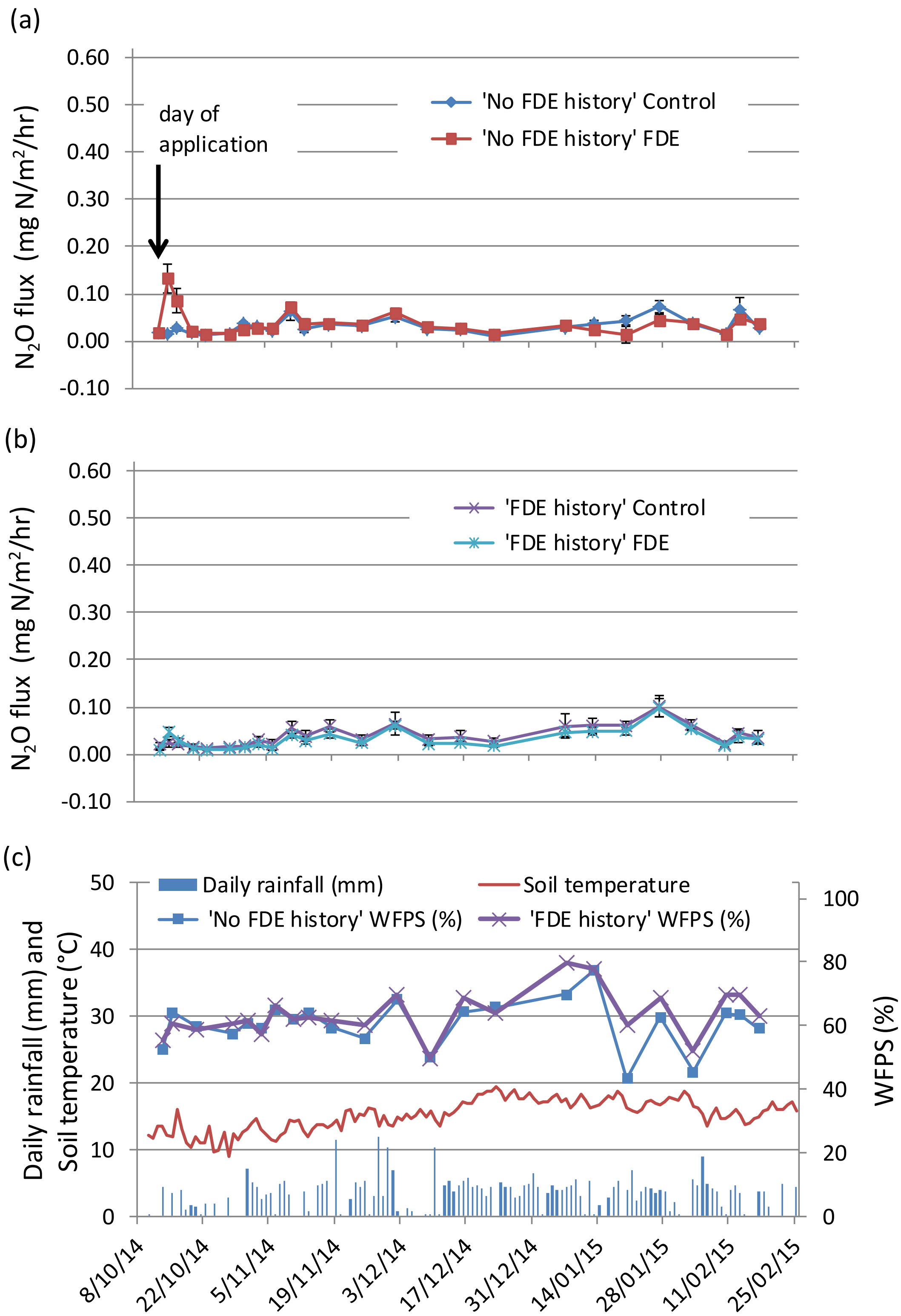

Figure 5. Canterbury site (a): N_2O flux (mg N/m^2/hr) from effluent applied to pasture with **(a)** no FDE history and **(b)** FDE history; errors bar indicate ± SEM. **(c)**: Daily rainfall (mm), soil temperature (°C; 5cm depth) and WFPS (%; 0-7.5cm).

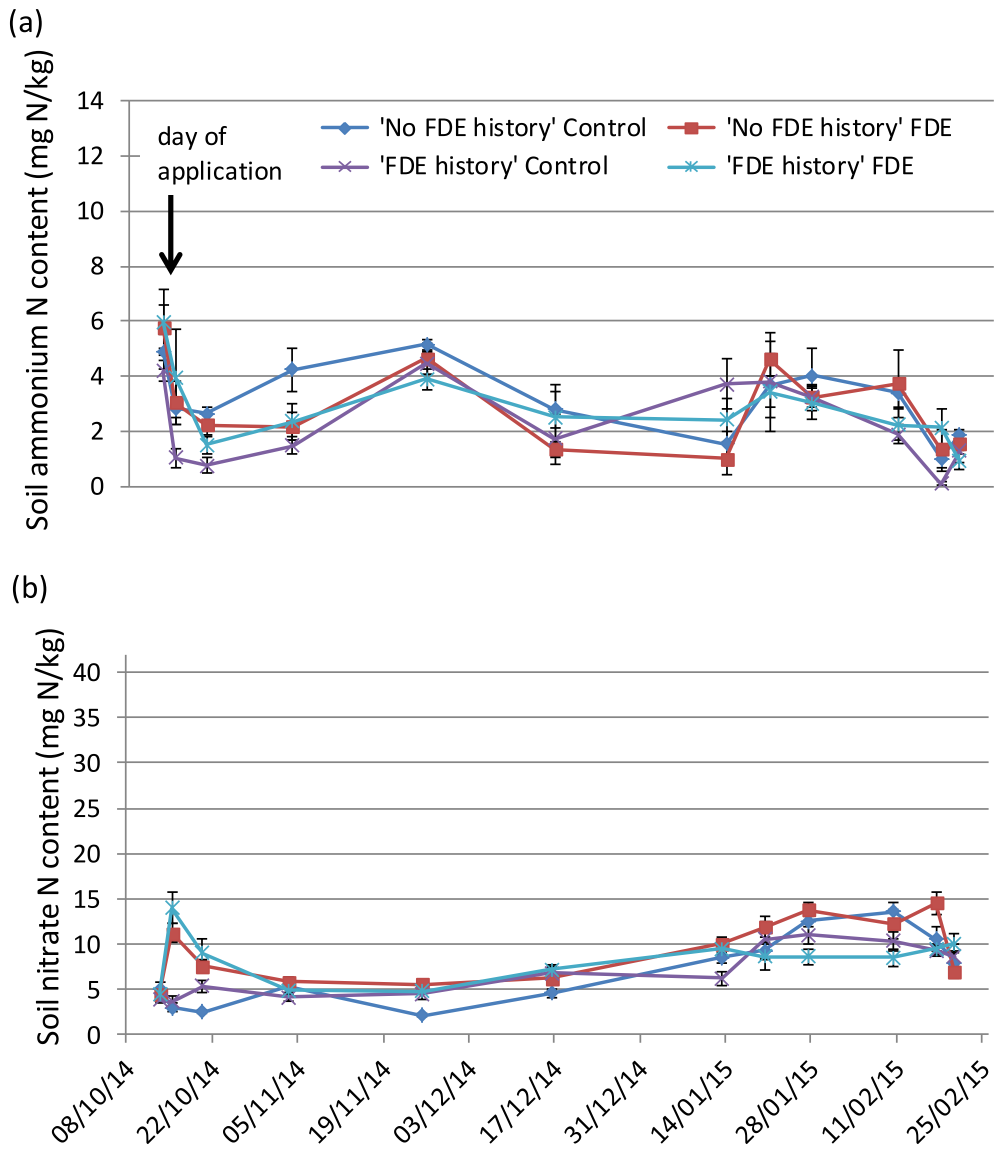

Figure 6. Canterbury site (a): Soil ammonium-N and **(b)** nitrate-N contents (mg N/kg; 0-7.5cm depth) measured at the 'no FDE history' and 'FDE history' sites.

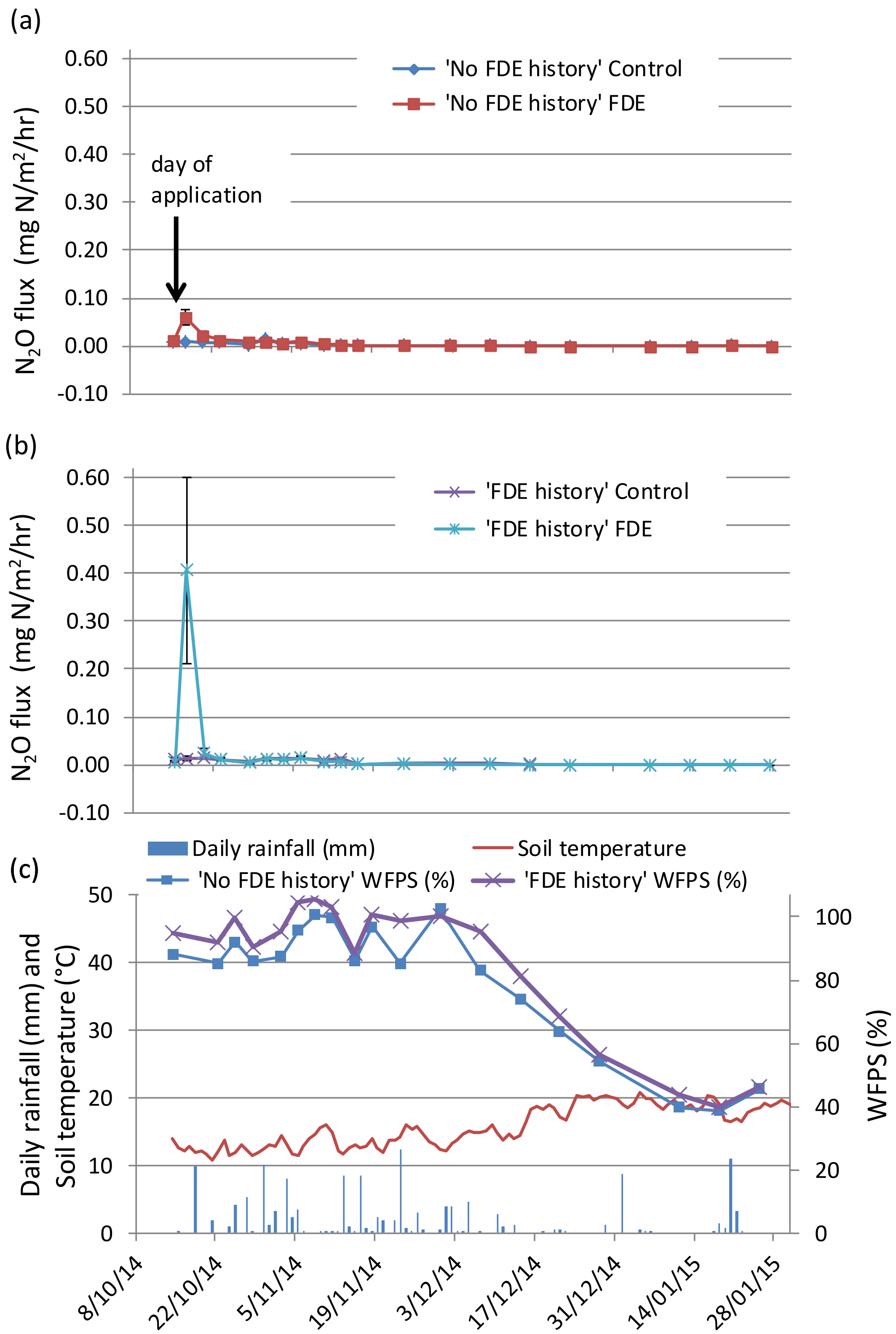

Figure 7. Otago site (a): N_2O flux (mg N/m^2/hr) from effluent applied to pasture with **(a)** no FDE history and **(b)** FDE history; errors bar indicate ± SEM. **(c)**: Daily rainfall (mm), soil temperature (°C; 5cm depth) and WFPS (%; 0-7.5cm).

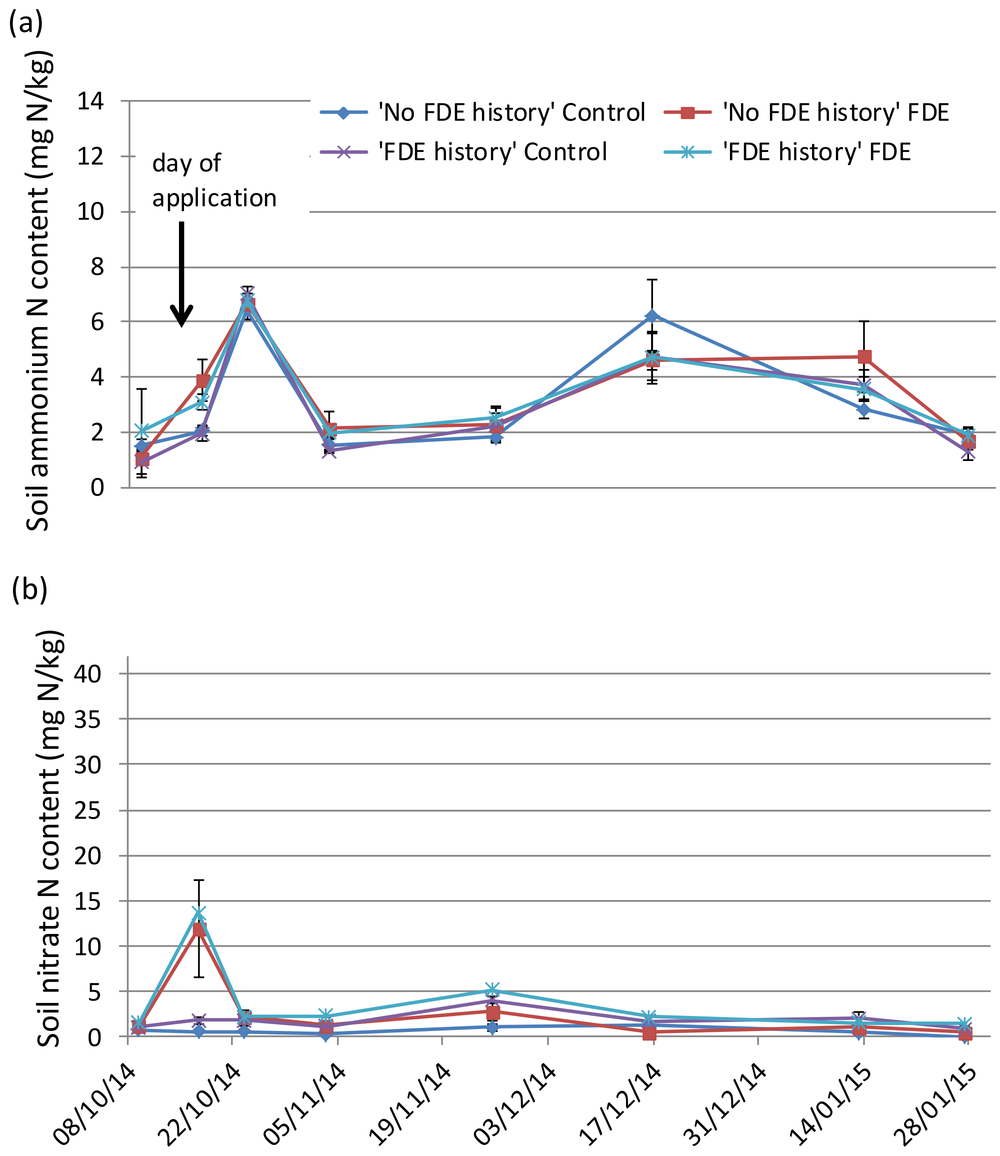

Figure 8. Otago site (a): Soil ammonium-N and **(b)** nitrate-N contents (mg N/kg; 0-7.5cm depth) measured at the 'no FDE history' and 'FDE history' sites.

4.2 Meta-analysis of EF_1

The database used for the meta-analysis of EF_1 included 26 urea fertiliser EF_1 values and 24 FDE EF_1 values, 4 of which were derived from the current study. Other FDE data was sourced from our earlier study (van der Weerden et al. 2014) and published research (Bhandral et al. 2007; Li et al. 2014, 2015) (Table 5). Data from two other New Zealand FDE EF_1 studies (Barton and Schipper 2001; Luo et al. 2008) were not included due to the relatively short duration of field measurements of N_2O emissions (less than 3 weeks). We suggest that measurement of N_2O emission factors from FDE should continue for at least 3 months due to potential mineralisation and subsequent nitrification of the organic fraction. The 26 urea EF_1 values included 22 analysed by Kelliher et al. (2014) plus 4 additional urea EF_1 values reported in our earlier study (van der Weerden et al. 2014). We excluded all urine and dung data (EF_3) for this updated analysis, as the combined dataset of 50 values was considered sufficient for a separate meta-analysis.

Table 5: N_2O emission factors resulting from land application of FDE.

Region	Effluent history (years)	Total N applied (kg ha^{-1})	Duration of monitoring after application (d)	EF_1 (%)	Study
Manawatu	0	61	102	0.4 [a)]	Bhandral et al. (2007)
	0	22	102	0.9 [b)]	
	0	49	56	0.2 [a)]	
	0	13	56	0.2 [b)]	
Waikato	0	96	172	0.14 [a)]	Li et al. (2014)
	0	74	172	0.03 [b)]	
Waikato	0	58	370	0.11 [a)]	van der Weerden et al. (2014)
Manawatu	0	52	366	0.78 [a)]	
Canterbury	0	56	366	0.06 [a)]	
Otago	0	57	367	0.14 [a)]	
Waikato	0	98	144	1.65 [a)]	Li et al. (2015)
	0	60	144	0.80 [b)]	
	0	101	143	0.01 [a)]	
	0	53	143	0.25 [b)]	
	0	101	110	0.56 [a)]	
	0	100	110	0.27 [b)]	
Waikato	0	54	105	0.28 [a)]	This report
	20	54	105	0.04[a)]	
Manawatu	0	28	106	0.20 [a)]	
	25	28	106	0.94 [a)]	
Canterbury	0	43	126	0.06 [a)]	
	14	43	126	0.12 [a)]	
Otago	0	46	103	0.29 [a)]	
	10	46	103	0.75 [a)]	

[a)] Fresh FDE
[b)] Stored FDE

The overall mean EF_1 for the combined FDE and urea fertiliser data was calculated as 0.48%, with a lower and upper 95% confidence interval of 0.00% and 1.32% (Table 6). There was no significant difference in the EF_1 values for FDE and urea EF_1 ($P > 0.05$), which were calculated from the combined data as 0.26% (0.00% – 1.12%) and 0.59% (0.00% – 1.48%), respectively, where values in brackets refer to the lower and upper 95% confidence interval.

Table 6: Best linear unbiased predictors (BLUPs) for direct nitrous oxide emission factors (n) of two N sources.

N source	Mean (%)	95% confidence interval (%)
FDE	0.26 (24)	0.00 – 1.12
Urea fertiliser	0.59 (26)	0.00 – 1.48
Combined FDE and urea fertiliser EF_1	0.48 (50)	0.00 – 1.32

5. Discussion

5.1 Nitrous oxide emissions and EF_1 values from FDE applied to pastures with and without a history of effluent irrigation.

Farm dairy effluent contains a supply of readily available N and labile C and a high water content that can lead to anaerobic zones within an aerobic soil immediately after application (Barton and Schipper, 2001; Bhandral et al. 2007). Under such conditions, N_2O production via both nitrification and denitrification can occur. In the current study, the TAN content of the FDE ranged from 42 - 62% of total N, while total solids ranged from 0.3 – 2.1%. As observed in previous studies (Bhandral et al. 2007; van der Weerden et al. 2014), N_2O fluxes were high from FDE within 1 to 3 days of application. These initial fluxes can be greater than those observed from N fertiliser or urine due to enhanced denitrification activity stimulated by increased C supply and/or decreased soil aeration following an increase in soil respiration (Barton and Schipper 2001; Pelster et al. 2012). The relatively rapid reduction in N_2O fluxes following the peak emissions observed at some of the experimental sites was likely to be due to the relatively low rates of readily available N applied in the FDE, which ranged from 17 to 29 kg total ammoniacal-N/ha (calculated from Table 2). For N_2O flux measurements, FDE was applied uniformly within the chamber base area, but not to the adjacent area outside of the base. The bases were inserted to a depth of approximately 100 mm, which will have reduced the risk of lateral movement of the FDE water beyond the chamber area. This risk was further minimised by the shallow depth of FDE applied (10 mm) and the moderate to high soil moisture content (between 55 and 98% WFPS across all sites) during the first month of the trials. Under these conditions, it is unlikely that the N_2O fluxes were influenced by the method used for FDE application.

We did not detect a significant difference in cumulative N_2O emissions from the FDE treatments and control treatments in three of the four regions (Table 3). This was likely due to the low rate of readily available N applied (as noted above) and the large spatial variation in emissions from both the FDE and control plots (Table 3). In contrast, the cumulative N_2O emissions from the FDE treatments at the Otago sites were significantly higher than from the control treatments at both the 'no FDE history' and 'FDE history' sites. This may be partly due to the lower spatial variation within treatments in this region, although it is important to note that the FDE treatment effect is reliant on a single large N_2O peak measured from the FDE treatment at both sites (see Figure 7a and 7b). This result should therefore be treated with caution.

Waikato and Canterbury produced the highest cumulative N_2O emissions, from both control and FDE treatments at the 'no FDE history' and 'FDE history' sites. In contrast, Otago produced the lowest cumulative emissions. This difference was likely due to the rainfall over the first 3 months producing WFPS values of ~73% and ~64% in Waikato and Canterbury, respectively, suitable for both nitrification and denitrification processes to occur. In contrast, while the Otago sites received less than half the rainfall of the other two regions, the sites were poorly drained gley soils with WFPS averaging 95% in the first month, and 77% in the first 3 months. This soil also contained an unusually high soil C content, which together with the wet soil conditions, will have been conducive for complete denitrification of NO_3^- to N_2. The Manawatu sites produced cumulative N_2O emissions that were greater than those from Otago, but less than the Waikato and Canterbury losses, probably due to the sites being located on a sandy loam soil with a low soil organic C content (1.4 – 2.5%) and having a relatively low WFPS (average of 56%) in the first 3 months.

There was no significant effect of paddock history on the cumulative N_2O emissions measured in Waikato, Manawatu and Canterbury (Table 3). In contrast, cumulative N_2O emissions from the FDE and control treatments in Otago were significantly greater from the 'FDE history' site compared to the 'no FDE history' site. As noted above, this difference between regions may be partly due to the lower spatial variation within treatments in Otago. For example, the difference in cumulative emissions from the FDE treatment between the two paddock histories in Manawatu, Canterbury and

Otago were similar, at about 310 – 350 g N_2O/ha, although the associated 95% confidence intervals overlap for the first two regions, but not for the Otago dataset (Table 3). This may be a function of lower variation between replicates when emissions are low, and suggests greater replication may be required in future experiments of this type.

Paddock FDE history did not affect the magnitude of EF_1. All four regions showed that there was no significant difference in EF_1 between soils that have not received previous FDE applications and soils that have received FDE for more than 10 years. This was one of the key objectives of the current study, because we were unsure if 10 or 20 years of effluent application would alter the soil microbial population and/or activity, thereby influencing N_2O emission factors. We did, however, observe that cumulative emissions were greater from the 'FDE history' site than the 'no FDE history' site in Otago. But as both the control and FDE treatments were equally affected, there was no resulting difference in EF_1 between the two sites. We ensured field sites within each region were located on the same farm. A further objective was to ensure the 'FDE history' sites had a similar number of years of receiving FDE, however our ability to achieve this objective was influenced by the region's general history of effluent management and the availability of suitable farms. Consequently, effluent history varied from 10 years in Otago to approximately 25 years in Manawatu (for the latter region, the farmer could not provide an exact number of years, suggesting it was '20-30 years'). We also attempted to stay with the same soil type at both sites within each region. Our study suggests a single country-specific EF_1 value can be calculated for effluent application to dairy pastures in New Zealand, regardless of the number of years paddocks have received effluent.

The arithmetic mean FDE EF_1 value across the 8 experiments in the current study was 0.34% ± 0.12% (mean ± SEM; n = 8). This is similar (not significantly different, $P > 0.05$) to the results of our previous study, where FDE EF_1 averaged 0.27% ± 0.17% across 4 experiments (van der Weerden et al. 2014). Emission factors measured in our current and previous study lie within the range of values (<0.1 to 1.2% of N applied) reported for effluent and slurry (Bhandral et al. 2007; Chadwick et al. 2011; Velthof and Mosquera, 2011; Li et al. 2014, 2015; Misselbrook et al. 2014; Rodhe et al. 2015).

5.2 Country-specific EF_1 values for FDE and urea fertiliser

Kelliher et al. (2014) conducted a meta-analysis of field experimental results to calculate a country-specific EF_1 value for urea fertiliser and EF_3 values for cattle and sheep excreta. Their meta-analysis did not include FDE as a source of N_2O, as the available dataset relevant to an EF_1 calculation at that time was limited to a single study: Bhandral et al. (2007). However, the recent increase in field studies quantifying FDE EF_1 values (Li et al. 2014, 2015, van der Weerden et al. 2014, and the current study), resulting in the number of FDE EF_1 values increasing 6-fold from 4 to 24 (Table 5), justified a meta-analysis of EF_1 for urea fertiliser and FDE.

New Zealand has adopted a country-specific emission factor $EF_{3\ PRP}$ of 1% for urine and 0.25% for dung (Ministry for the Environment, 2014). New Zealand also currently adopts the IPCC default value of 1% for effluent applied to soils. Considering FDE is a mixture of urine and dung, diluted with water, one could expect the emission factor for FDE would be less than 1%.

The analysis has shown that the EF_1 value for FDE is lower, albeit not significantly, than for urea fertiliser. Approximately 50% of the total N in FDE is in the organic form with the remaining N as ammonium (see Table 2; similar FDE characteristics also measured in earlier studies). In contrast, as N in urea fertiliser is 100% readily available, it may be possible that the nitrogen use efficiency (NUE) of urea is slightly lower than FDE when applied at similar total N loadings due to an overall slower supply of FDE N to the soil-plant system. A lower NUE may increase the risk of gaseous N losses including N_2O. This difference in N composition may explain the difference in EF_1 values for these two N sources, although, as mentioned, this difference was not significant based on the currently available data. Of course, a more robust comparison would be where both N treatments are applied to pastures in the same trial. Such a comparison was included in our earlier study (van der Weerden et al., 2014), where N_2O emissions from FDE were measured over a 12 month period to ensure any emissions following slow mineralisation of organic N in FDE were included. In that study, the resulting EF_1 for urea was approximately double that for FDE. Both N forms were applied at similar rates (30-50 kg N/ha), and therefore the difference in EF_1 was unlikely to be related to N loading. This supports the hypothesis that the EF_1 value estimated for urea fertiliser is greater than for FDE.

New Zealand's lower mean EF_1 value for urea (0.59%) compared to the IPCC mean default value of 1% is probably due to the fertiliser form and rate, as discussed in our earlier report (van der Weerden et al. 2014). These results suggest the value of 1% is too high under New Zealand's farming practices, as we typically apply small (*ca* 30-50 kg N/ha/application) fertiliser dressings as urea. There have been several overseas studies reporting lower EF_1 values for urea and NH_4^+-based fertilisers compared to the IPCC 2006 guidelines default value of 1% (IPCC, 2006). The Netherlands has adopted an EF_1 value of 0.5% for urea and NH_4^+-based fertilisers applied to mineral soils (Kuikman et al. 2006). While Australia continues to adopt an EF_1 value of 1.0% for N fertiliser, studies on Australian pasture have indicated urea fertiliser EF_1 values of 0.47% and 0.5% (Galbally et al. 2005; Chen et al. 2010).

New Zealand currently adopts a urea fertiliser EF_1 value of 0.48%, based on a meta-analysis of combined urine, dung and urea data (Kelliher et al., 2014). Our revised meta-analysis of urea fertiliser EF_1 excluded the influence of urine and dung data, but included the influence of FDE EF_1 data, which was found to be more similar to urea. The revised urea fertiliser EF_1 value of 0.59% is greater than the earlier analysis of 0.48% for two reasons: (1) the effect of 4 additional data values from the current study and (2) the effect of a bias correction on EF values, as part of the statistical analysis for determining EF values. The bias correction, applied to both analyses (Kelliher et al. 2014 and the current study), ensures the ratios of estimated EF values between N sources are preserved.

The most common type of manure applied to land in New Zealand is FDE (Laubach et al. 2015). Farm dairy effluent is more dilute with a lower N content compared to slurries commonly applied to soil in the Northern Hemisphere. However, application of cattle slurry to grassland produces a similar range of EF_1 values to FDE. Velthof and Mosquera (2011) surface applied cattle slurry to grassland over three years at an equivalent rate of between 274 and 332 kg N/ha, resulting in EF_1 values of between 0 and 0.2%, averaging 0.1%. Misselbrook et al. (2014) applied cattle slurry to grassland in four experiments, where rates ranged from 106 to 181 kg N/ha. Three of the experiments resulted in EF_1 values of between 0.04% and 0.23%, while 1.15% was measured in the remaining experiment. Bourdin et al. (2014) conducted a study in Ireland, where grass-fed cattle slurry was applied to grassland on 4 occasions from spring to summer to determine if EF_1 was affected by total solids (TS) content. Slurry was applied at an equivalent rate of between 26 and 67 kg N/ha, a similar range to the N loadings used in New Zealand studies (Table 5). These workers found that TS content had no significant effect on EF_1, which averaged 0.67% across the 4 slurry applications.

For the purpose of calculating an accurate New Zealand agricultural greenhouse gas inventory, we recommend separate single-country EF_1 values are used for FDE and urea fertiliser. We also recommend EF_1 values are based on the results of the combined EF_1 meta-analysis. Lastly, we recommend the EF_1 values are presented to one decimal place, given the large range in the confidence intervals calculated for each N source. On this basis, we recommend MPI adopt an EF_1 value of 0.3% for FDE and 0.6% for urea fertiliser. For the latter N source (urea fertiliser), we suggest the value of 0.6% is used in place of the recently adopted value of 0.48% (Ministry for the Environment, 2015), as the updated analysis excludes the influence of animal excreta EF_3 data. The earlier analysis by Kelliher et al. (2014) included both EF_1 and EF_3 data.

6. Summary and Recommendations

This report presents recommendations for EF_1. This was based on (1) the findings of a research experiment conducted across New Zealand to quantify EF_1 under contrasting soil and climatic conditions, and (2) a meta-analysis of EF_1 using FDE data from the current study and FDE- and urea fertiliser- EF_1 data from previous NZ studies to determine country-specific EF_1 values.

Objective 1: Determine EF_1 for FDE applied to pastures with and without a history of receiving FDE.

- Effluent irrigation history had a significant effect ($P < 0.01$) on cumulative N_2O losses measured in Otago; however there was no significant effect of effluent history in all other regions ($P > 0.05$).
- Effluent history had no effect on FDE EF_1 in all regions ($P > 0.05$).
- The arithmetic mean FDE EF_1 was 0.34% ± 0.12% (mean ± SEM, n=8).

Objective 2: Determine country-specific EF_1 values for FDE and urea fertiliser by conducting a meta-analysis of relevant data.

- Combining the results from the four regional experiments in objective 1 with data from 20 other regional FDE trials and 26 regional urea fertiliser trials indicated an overall mean EF_1 value of 0.48%, with a lower and upper 95% confidence interval of 0.00% and 1.56%.
- There was no significant difference in the EF_1 values for FDE and urea ($P > 0.05$), which were respectively calculated from the combined data as 0.26%

(0.00% – 1.12%) and 0.59% (0.00% – 1.48%) (ranges represent lower and upper 95% confidence intervals).

Recommendations

- That separate single-country EF_1 values are used for FDE and urea fertiliser, due to the difference in characteristics of the two N sources. Urea is a readily available source of N while FDE contains both organic N and readily available ammoniacal-N.
- That MPI adopt an EF_1 value of 0.3% for FDE and 0.6% for urea fertiliser in future New Zealand agricultural greenhouse gas inventories.

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