Quantification of nitrous oxide emissions and emission factors from beef and dairy cattle excreta deposited on grazed pastoral hill lands

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Abstract

Excreta deposition by grazing livestock is the single largest source of agricultural nitrous oxide (N₂O) emissions in New Zealand (NZ). N₂O emissions and emission factors (EF₃; percentage of excreta nitrogen emitted as N₂O) from sheep, beef- and dairy-cattle excreta deposited can vary with differences in the hill land slope and disaggregation of EF₃ based on slope may therefore result in a more accurate and improved inventory of national N₂O emission. However, research data on N₂O emissions from dairy cattle grazing on low and medium slopes of hill country or for beef cattle on low slopes is scarce. Field trials were therefore conducted in four regions of NZ on dairy-grazed (three regions) or sheep & beef cattle-grazed hill land (one region). N₂O emissions were measured following dairy and beef cattle urine and dung application on low and medium sloping land in late autumn. Application of either cattle urine or dung increased N₂O emissions which mostly varied with excreta type (urine vs dung), slope class (low vs medium) or region. However, there was no significant slope-effect for EF₃ values for beef and dairy cattle excreta (urine or dung) from each individual region, or combined from the three dairy-grazed sites. These findings confirm our hypothesis that N₂O EF₃ values for excretal inputs on established dairy hill land on low and medium slopes are similar for
dairy-grazed hill land. However, the sheep & beef cattle grazed sites had lower EF₃ for excreta deposited on medium slope land than for excreted deposited on low slope land. Our results help the refinement of NZ’s country-specific variations in EF₃ to improve the accuracy and transparency of farm-, regional- and national-scale N₂O inventories. In addition, our findings could help farmers and policy-makers to devise strategies for reducing N₂O emissions, by targeting mitigation technologies to areas and sources with high EF₃.

**Keywords**

Nitrogen transformation, Greenhouse gas, Inventory improvements, Farm-scale, National-scale, Agriculture, Mitigation

**1. Introduction**

Globally, agricultural soils contribute about 65–70% of the total greenhouse gas (GHG) nitrous oxide (N₂O) produced by terrestrial ecosystems (Ussiri & Lal 2013). As a powerful GHG, N₂O has the global warming potential of 298 times of that of carbon dioxide (CO₂) and contributes to stratospheric ozone depletion (IPCC 2007, 2013). Livestock farming accounts for an estimated 2.1 Gt CO₂-eq of N₂O per annum, or 53 % of anthropogenic N₂O emissions, which corresponds to 39.3% of total agricultural emissions (FAO 2015). New Zealand has the third highest per capita GHG emissions in the world due to the comparatively high number of ruminants per head of population; ruminants produce methane via digestion of forages in the rumen and N₂O from soils where their excreta is deposited (MfE 2016). Grazed pasture soils exhibit high potential for N₂O emissions from urine deposited by grazing livestock, and are
the primary source of direct and indirect N₂O emissions, contributing c. 64% of New Zealand’s 8.59 Gg CO₂e agricultural N₂O emissions and 14.2% of emissions from agriculture sector (MfE 2018).

A series of studies focusing on measuring New Zealand specific N₂O emissions from sheep, beef- and dairy-cattle excreta deposited on different topographies have been conducted (e.g. van der Weerden et al. 2011; Hoogendoorn et al. 2013; Luo et al. 2013, 2016). Most of the excreta N deposited onto grazed land is in the form of urea existing in the urine, while organic N forms are deposited in the dung (Selbie et al. 2015; Chadwick et al. 2018). Hydrolysis of urea and mineralisation of organic N to ammonium (NH₄⁺) provide a pool of available nitrogen (N) for the nitrification and denitrification processes, which are the main mechanisms for N₂O production (Zhou et al. 2017). N₂O production is influenced by multiple factors, including availability of N, soil aeration, pH and environmental conditions (Firestone & Davidson 1989; Groffman & Tiedje 1991; Whalen et al. 2000; Xu et al. 2008). In grazed hill lands, slope influences soil characteristics, pasture production, its N content and N uptake, excreta deposition and environmental conditions such as soil bulk density, depth, moisture and fertility (Saggar et al. 1990, 2015; Mackay et al. 1995; Luo et al. 2013). Research has shown that N₂O emissions and emission factors (EF₃, percentage of deposited excreta N emitted as N₂O) from steeper slopes are generally less than those from lower slopes and from flatland (e.g. de Klein et al. 2009; Hoogendoorn et al. 2013; Luo et al. 2013, 2016; Saggar et al. 2015). A meta-analysis also confirms that the EF₃ values for animal urine and dung deposited on medium (12 - 25°) slopes are significantly lower than those from low (0 - 12°) slopes (Kelliher et al. 2014).
The on-going intensification in dairying has, in some instances, lead to dairy cattle now grazing hill country medium slopes. Disaggregation of EF3 for urine and dung of different animals from different slope levels can provide a more accurate inventory of national N2O emission. Indeed, the effect of land slope on the N2O EF3 for urine and dung on direct N2O emissions from excreta deposited by sheep, beef, and deer is likely to be incorporated into New Zealand’s national GHG inventory soon. However, there is no research data available on N2O emissions from dairy cattle grazing on low and medium slopes of hill country, while limited data exists for beef cattle urine and dung on low slopes. Thus, the hill slope EF3 values for dairy and beef categories are less robust and leave a gap for adoption of the proposed changes to the inventory methodology (Saggar et al., 2015). We hypothesize that N2O EF3 values for excretal inputs on established dairy hill land low and medium slopes or beef cattle grazing on low slopes would be similar due to improved soil fertility from intensified land use on these slopes.

The objectives of this study were to: i) determine N2O emissions and EF3 values from dairy and beef cattle urine and dung on low (<12°) and medium hill land slopes (12 - 25°) of sheep & beef cattle-grazed and dairy-grazed pastures; and ii) contribute to the refinement and completeness of the proposed new methodology (Saggar et al. 2015) for incorporation into New Zealand’s agricultural GHG inventory.

2. Materials and methods

2.1. Site and soil description

Four trial sites were selected across the range of climatic conditions in Northland, Waikato, Manawatu and Otago regions throughout NZ (Fig. 1). The trials in the Northland, Waikato and
Manawatu regions were located on pastures that had been used for dairy and/or beef cattle grazing, while the trial in the Otago region was on sheep & beef cattle grazing hill country farm. To represent the most prevalent soil type in each region, the Waikato, Manawatu and Otago field trials were conducted on freely drained soils, while the Northland field trial was conducted on a poorly drained soil (Table 1). All the sites were fenced off and stock excluded at least 6 weeks before the commencement of the field trials to avoid interference from fresh dung and urine inputs and reduce spatial variability from the previous uneven deposition of dung and urine.

2.2. Treatments

Trials at the Northland and Manawatu sites commenced in early winter 2016, while trials at the Waikato and Otago sites commenced in early winter 2017. Excreta treatments, including dairy cow urine, beef cattle urine, dairy cow dung, and beef cattle dung, were applied to both low (< 12°) and medium (12° - 25°) slope areas at each trial site. A control with no animal-excreta treatment was also included. The treatments were assigned to the plots in a randomized block design with 5 replicates of each treatment. Plot size was about 1.5 x 1.0 m for all treatments, and there was an additional buffer zone of at least 0.5 m between adjacent plots. At four of the five blocks in each slope class, separate sub-plots within each plot received the same treatments as for N₂O measurements. These were used for destructive soil sampling. Real excreta were applied for N₂O measurements, and artificial urine (de Klein et al. 2003 and real dung were applied to the separate soil sampling sub-plots.

2.3. Excreta collection
Fresh urine and dung for the treatments were collected from dairy- and from beef-cattle grazing pastures with the formal approval from the AgResearch Animal Ethics Committee. Urine was collected from dairy cows on the rotary platform during milking, and from beef cows brought to a yarding area, by holding a collection vessel behind the cows as they urinated. Dairy and beef cattle dung was collected from nearby stock-grazed paddocks on local farms. Immediately following excreta collection, sub-samples of beef cattle and dairy cattle urine or dung were analysed for their properties (Table 2). The urine and dung were stored at 4°C for up to three days before field application.

2.4. Excreta N application rate

On low slope areas, the application rate for dairy and beef cattle urine was 10 L/m². On medium slope areas, the urine application rate was 6.7 L/m² to account for an estimated 33% runoff of urine in these areas (Luo et al. 2013), resulting in reduced specific N loading rates (Table 2). The dung application rate was 28.3 kg/m² on a fresh weight basis. There was no difference in the target rate of dung N applied on low and medium slope areas, as, unlike urine, run-off was not considered to be an issue for dung deposited on slopes. Urine was applied slowly and evenly to the entire plot to prevent urine runoff, while dung was applied evenly to a 0.5 × 0.5 m area within the larger 1.5 × 1.0 m plot.

2.5. Nitrous oxide measurement

A static chamber technique was used to measure N₂O emissions, and the methodology was based on that used the previous published studies on excreta N₂O emissions (de Klein et al.
One week before the trial began, static chamber bases (23-25 cm diameter) were inserted 50-100 mm into the soil in each plot. Gas samples were taken from each chamber to determine the spatial variability of background N₂O flux between the plots and to assist with interpretation of patterns of N₂O flux from individual sampling plots post treatment application. Following the treatment applications, measurements were carried out twice a week for the first 4 weeks and thereafter weekly. The measurements continued till the N₂O flux values and soil mineral N content for treatment plots reached the background levels measured in the control plots. During weekly phases of N₂O flux measurement, additional sampling occurred as soon as practical following rainfall events of greater than 10 mm of rain in a previous 24 hrs period. On each sampling day, N₂O measurements were carried out between 10 am and 12 noon. Gas samples from chamber headspace were taken during a cover period of 60 minutes at times t₀, t₃₀ and t₆₀ (or similar) for the first nine gas sampling occasions and during a cover period of 45 minutes (or similar) at times t₀ and t₄₅ for the remainder of the sampling occasions. On each sampling day at each site, two background atmosphere samples were also taken.

Nitrous oxide concentration of gas samples was analysed by gas chromatography using a Shimadzu GC-17a gas chromatograph equipped with a $^{63}$Ni-electroncapture detector (oven, valve and detector temperatures were operated at 65, 100 and 280 °C, respectively) using oxygen-free N as a carrier gas and connected to an automatic sampler capable of handling up to 120 samples using an SRI 8610 automated gas chromatograph (de Klein et al., 2003; Saggar et al. 2004; Hedley et al. 2006; Luo et al. 2015). The increase in N₂O concentration within the chamber headspace, for the gas samples collected at t₀, t₃₀ and t₆₀ were generally linear ($R^2 >0.90$). Therefore, the hourly N₂O fluxes were calculated (Mosier & Mack, 1980) using linear regression and the ideal gas law according to Equation 1:
where, $F$ is the hourly $N_2O$ fluxes (mg N m$^{-2}$ h$^{-1}$); $\delta N_2O$ is the increase in head space $N_2O$ over time (µL L$^{-1}$); $\delta T$ is the enclosure period (hours); $M$ is the molar weight of N in $N_2O$; $V_m$ is the molar volume of gas at the sampling temperature (L mol$^{-1}$); $H$ is the height of headspace (m).

The hourly flux data were integrated over time, for each enclosure, to estimate the total emissions over the measurement period. Emission factors ($EF_3$, $N_2O$-N emitted as % of excreta N applied) were calculated using Equation 2:

$$EF_3 = \frac{N_2O_{excreta} - N_2O_{control}}{excreta \text{ N applied}} \times 100\%$$

where, $EF_3$ is emission factor ($N_2O$-N emitted as % of urine-N or dung-N applied), $N_2O_{excreta}$ and $N_2O_{control}$ are the cumulative $N_2O$-N emissions from the urine/dung and control plots, respectively (kg N ha$^{-1}$), and excreta N applied is the rate of urine N or dung N applied (kg N ha$^{-1}$).

2.6. Soil and climatic parameters

At the start of each trial, a bulk soil sample comprising 12 soil cores was collected from each trial site for soil chemical analysis, including pH, Olsen P, total Kjeldahl N and organic carbon, while at least 10 other intact cores from each site were collected for soil bulk density determination. The soil chemical and physical properties are shown in Table 1. In general, Olsen P, organic matter and total N were high in soil on low slopes compared to medium slopes in each of the four regions. The Northland low slope area had a very high Olsen P level at 66 µg ml$^{-1}$. Soil bulk densities were higher on medium- compared to low-slope areas at the
Northland and Otago sites, but similar between the two slopes at the Waikato and Manawatu sites.

Following the treatment application, soil mineral N measurements, including NH$_4^+$-N and NO$_3^-$ N content, were carried out once per week in Waikato, while a less intensive sampling regime was used for the remaining sites with approximately 6-9 determinations made throughout the entire trial. Soil water content was measured for all plots when gas samples were collected. Soil mineral N were analysed using three soil cores collected from soil sub-plot of each plot in all treatments and extracted in 2 M KCl. Gravimetric water content was measured using two soil cores collected from each plot dried at 105°C for 24 h, or volumetric water content was determined by time domain reflectometry (TDR). When TDR was used, soil moisture determination from mineral N sampling and soil bulk density was used to calibrate TDR readings. Water-filled pore space (WFPS) was calculated by dividing volumetric water content by total porosity (Linn and Doran, 1984). The depth of all the soil samples was 7.5 cm, and diameters of soil samples for chemical analysis and bulk density were 2.5 and 10 cm, respectively.

Daily rainfall and ambient air and soil temperature were recorded for the entire trial period. Rainfall between sampling days was determined with a manual rain gauge installed in each site.

2.7. Statistical analysis

Differences in the EF$_3$ values between treatments were analysed using the statistical software package GenStat® for Windows® 13th edition. EF$_3$ data, across all regions and sites, were found
to be highly skewed with non-constant variance. Therefore, the EF$_3$ data were square root
transformed prior to the analysis. The reported EF$_3$ values were obtained following back-
transformation.

3. Results

3.1. Climatic conditions

During the first six weeks of post excreta application, total rainfall at the Northland, Waikato,
Manawatu and Otago sites were 189, 177, 182 and 85 mm (Fig. 2). Daily mean soil
temperature (10 cm depth) increased at the Northland, Manawatu and Otago sites, while it
did not change much at the Waikato site (Fig. 2). During the first six weeks of post excreta
application, mean soil temperatures were highest (12.7°C) at the Northland site and lowest
(below 6°C) at the Otago site, while the Waikato and Manawatu soil temperatures were
intermediate at about 9 - 12°C.

3.2. Nitrous oxide emissions

3.2.1. Background nitrous oxide fluxes

Background N$_2$O fluxes, measured just before treatment application, were generally higher in
the low-slope areas than in the medium areas, with the highest baseline N$_2$O flux being at
2.18 mg N m$^{-2}$ d$^{-1}$ on the Northland low slope and the least baseline N$_2$O flux being at 0.024
mg N m$^{-2}$ d$^{-1}$ on the Otago medium slope (Fig. 3). For all four regions, average background
N$_2$O emissions from the measured areas that had no excreta applied (i.e. the control
treatments) were about 1.28 and 0.17 kg N$_2$O-N ha$^{-1}$ over the 4 to 6 months (winter/early-
spring) measurement period for the low and medium slopes, respectively (Fig. 4). The highest
emission value (4.03 kg N$_2$O-N ha$^{-1}$) was found at the Northland site, while the lowest
emissions (0.02 kg N$_2$O-N ha$^{-1}$) were found from the medium-slope area at the Otago site.

3.2.2. Nitrous oxide emissions from urine and dung

Application of either urine or dung increased N$_2$O fluxes, but the patterns and magnitudes of
the increases were not consistent between excreta types, slope classes or regions (Fig. 3). The
largest increase in N$_2$O flux was from dairy cattle urine on the low slope in the Northland site
(432 mg N m$^{-2}$ d$^{-1}$) and the smallest increases in the Otago site, with higher N$_2$O fluxes being
generally observed on low slopes than on medium slopes in all regions. N$_2$O fluxes from dairy
or beef cattle dung were generally low at both low and medium slopes at all four sites (Fig.
3). Total N$_2$O emissions from dairy urine were 3.0 -11.5 kg N$_2$O-N ha$^{-1}$ in Northland, 2.0 to 8.9
kg N$_2$O-N ha$^{-1}$ in Manawatu, 0.67-1.07 kg N$_2$O-N ha$^{-1}$ in Waikato, and 0.3-2.7 kg N$_2$O-N ha$^{-1}$ in
Otago. Similar magnitudes of the total N$_2$O emissions were also found from beef cattle urine
in the respective regions.

3.3. Soil mineral-N and moisture conditions

Soil concentrations of NH$_4^+$-N and NO$_3^-$-N in the control treatments were generally low for
both slope areas in all four trial sites throughout the sampling period (<20 mg N kg$^{-1}$ dry soil)
due to there being no extra mineral N input in control treatments (Fig. 3). Concentrations of
NH$_4^+$-N in the soil peaked either on the day of urine application or within several days after
urine application. Nitrification of urine N was rapid at the Northland and Waikato sites, as soil
NO$_3^-$-N concentrations peaked within a month post urine application. The peak NO$_3^-$-N
concentrations were generally much lower than the peak NH$_4^+$-N concentrations. Overall, soil NO$_3^-$-N concentrations for the Manawatu and Otago sites were generally low (<80 mg N kg$^{-1}$ dry soil) over the sampling period.

There was no increase in soil NH$_4^+$-N concentrations in the dung treated soils at either slope site in all regions except the Manawatu low slope, where soil NH$_4^+$-N concentrations in the dung treated soil increased about two months after treatment application (Fig. 3). NO$_3^-$-N concentrations in the cattle dung treated soils on both slopes in the Waikato and Northland regions peaked within two months of post excreta application. Soil NO$_3^-$-N concentrations at the Otago site increased during 3-4 months following cattle dung application on both slopes. The Manawatu site showed little change in NO$_3^-$-N concentrations after dung application throughout the trial period.

Soil WFPS values were similar on both slopes for all four regions (Fig. 3) and were not influenced by difference in rainfall among regions. Soils were over 70% WFPS for much of the 6-week period for both the Northland and Waikato sites, and were about 60% for the Manawatu site and 67% for the Otago site.

3.4. Nitrous oxide emission factors

Nitrous oxide emission factors for animal excreta for the Northland, Waikato, Manawatu and Otago region are presented in Table S1 (by region and slope class). These EF$_3$ values varied widely (0.048 – 1.30%) with no statistically significant differences in urine or dung EF$_3$ values between the two slope classes over all sites (0.79% vs 0.82% for urine on the low and medium slope, respectively; 0.31% vs 0.37% for dung on the low and medium slope, respectively). In Otago region, higher dung EF$_3$ values were observed on the low slope (0.573%) than on the
medium slope (0.229%). The sites in Northland and Manawatu region produced the higher
EF$_3$ values than the sites in Waikato and Otago regions (Table S1). Effects on EF$_3$ by slopes,
animal species and excreta types are presented in Table 3. The probabilities of a slope class
animal species ($P = 0.656$), slope class × excreta type and slope class × animal species effects
including slope class × animal species × excreta type were non-significant.

Analysis of the urine and dung EF$_3$ data (Table 4) showed different slope effects from the
dairy-grazed hill land farms (Northland, Waikato and Manawatu) than those from the sheep
& beef cattle-grazed hill farm (Otago). The EF$_3$ values were lower on medium slope (0.048-
0.157%) than on low slope (0.183-0.573%) for the sheep & beef cattle -grazed Otago site, with
no significant difference in EF$_3$ between low slope and medium slope for the dairy-grazed
pastures. When the combined EF$_3$ data from all 4 regions were analysed, there was a trend
for lower EF$_3$ for each excreta type on the medium slope (0.143-0.526%) than on the low slope
(0.162-0.708%) (Table 4). However, the analysis indicates that the slope class effect was not
statistically significant.

4. Discussion

4.1. Nitrous oxide emissions from cattle excreta on hill land

The current default New Zealand IPCC EF$_3$ values are 1% and 0.25% for animal urine and dung,
respectively (MfE, 2016). The average EF$_3$ values obtained over the measurement periods for
the four regions in this study (Table 4) are lower than these default annual EF$_3$ values. Rainfall
and soil drainage conditions affect soil WFPS and oxygen diffusivity, consequently influencing
microbe’s activity and regulating the N$_2$O emissions (Dobbie & Smith 2001; Saggar et al. 2004;
Eva et al., 2015; Lark & Milne 2017). Lower N$_2$O production potential of well-drained soils
used in Waikato, Manawatu and Otago compared with poorly drained Northland soil observed in these sites may be attributed to a lower denitrification (de Klein et al. 2003; Luo et al. 2013) or higher amounts of urine-/nitrate-N leaching beyond the rhizosphere zone, therefore resulting in lower EF$_3$. At the Waikato site, high rainfall during the first six weeks of the trial (Fig. 2) could have caused greater than average leaching of urine-/nitrate-N from the other two well drained soils, and/or complete denitrification to dinitrogen gas (N$_2$). The soil in the Otago region was drier, which may have led to lower denitrification rates. A significant and positive relationship between rainfall in the initial six weeks and the EF$_3$ data for cattle urine or dung was obtained in these trials (R = 0.71 for urine, R = 0.61 for dung, P < 0.05, n = 16), but measured average WFPS values during this period did not significantly correlate with the EF$_3$ values (R = -0.04 for urine, R = -0.36 for dung, P > 0.05, n = 16). These results differ from those reported by Kelliher et al. (2014), who found a significant relationship between EF$_3$ values and measured average WFPS values in the initial six weeks after application of excreta. These observed differences could probably reflect the differences in soil texture, soil drainage class and clay contents in the test soils.

In addition to poorly drained soil conditions and high WFPS, compared to Manawatu and Otago the higher EF$_3$ values in Northland appear to be caused by warmer temperatures (Fig. 3); in this study, there was a positive and significant relationship between EF$_3$ for urine and average soil temperature in the first six weeks after excreta application (R = 0.62, P < 0.05, n = 16). Warming of soil surface can enhance microbial transformations in the litter layer and surface soil, accelerating organic matter decomposition and supply more labile organic matter, and positively affect N$_2$O emissions (Dobbie & Smith 2001; Voigt et al. 2017). The relationship between EF$_3$ for dung and average soil temperature in the first six weeks after excreta application was positive, but not significant (R = 0.32, P > 0.05, n = 16).
A significant and positive relationship observed in this study between soil Olsen P levels and
the EF3 data for cattle urine (R = 0.42, n = 16) is similar to that reported for sheep urine was
in previous hill land field trials (Luo et al. 2013). Olsen P, as an indicator for soil fertility status
in legume-based New Zealand pastures (Tillman et al. 2012), might be associated with labile
N and C, and abundance and activity of soil microbes, which regulate excreta-induced N2O
emissions and background emissions (Hoogendoorn et al. 2013; Jha et al. 2017). However, the
absence of a significant relationship between soil Olsen P on background emissions and cattle
dung EF3 could be due to the low emission factors found for cattle dung (Table S1). It may also
be related to microorganisms, C and nutrients contained in deposited dung itself that could
regulate N2O emissions to some extent.

Application of animal excreta has been reported to stimulate N transformation reactions and
increase N2O emissions (van Groenigen et al. 2005; van der Weerden et al. 2011;
In this study, N2O fluxes also generally increased following excreta deposition, with the
magnitude of the increase being greater from both dairy and beef urine application than from
dung application (Figs. 3; 4). Compared to dung application, urine could rapidly supply
available mineral N for nitrification and denitrification through hydrolysis of the urea, leading
to higher N2O emissions (Todd & Hausinger 1989; Kaminskaia & Kostic 1997; Udert et al. 2003;
Hristov et al. 2011). However, N2O fluxes remained elevated for longer periods for the dung
treatments than for the urine treatments in most regions (Fig. 3), probably due to slow
formation of mineral N from decomposition of organic matter in dung (Horton et al. 1992;
The increased N\textsubscript{2}O fluxes generally coincided with increased soil NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N concentrations measured after excreta application (Fig. 3); however, N\textsubscript{2}O fluxes and soil mineral N content measured over the course of the experiments were not significantly correlated (P > 0.05). It is likely that most of the applied excreta N may have been taken up by plants, immobilised into the soil, leached out from the surface soil layers or lost to the atmosphere through ammonia volatilisation. This would consequently have reduced the amount of mineral N available for denitrification and N\textsubscript{2}O production. N\textsubscript{2}O fluxes are also regulated by soil WFPS (Luo et al. 2013). Soil WFPS is affected by rainfall and accordingly, the high N\textsubscript{2}O fluxes observed in this study generally coincided with rainfall events (Figs. 2; 3).

4.2 Effect of management history on EF\textsubscript{3}

The differences in the background N\textsubscript{2}O fluxes between the medium and the low slope sites, measured before treatment application may reflect differences in soil fertility status resulting from variable nutrient inputs caused by intensification of livestock farming at the sites (Table 1). The basic soil properties (Olsen P and OC) accounted for these, with the correlation coefficients (r) between background N\textsubscript{2}O fluxes and Olsen P and OC (0.96, 0.46 and 0.51, respectively). Soils with high fertility indicators (Olsen P and OC) generally indicate greater abundance and activity of soil microbes and potentially lead to higher level of mineralised N contributing to high N\textsubscript{2}O fluxes (Tillman et al. 2012).

The hill country soil used in the Otago region had lower fertility compared to the soils in the other three regions (Table 1), which is likely to have resulted in the observed lower EF\textsubscript{3} (Table 4 and S1). The Otago site had been under a sheep & beef grazing management regime. Higher EF\textsubscript{3} values on the low slopes than those on the medium slopes were also observed. These
differences may reflect lower excreta return on medium slopes influencing EF₃. The small difference in Olsen P (16 vs 14 µg ml⁻¹, Table 1) would suggest soil fertility was similar on the two slopes in this region. The results of this study are consistent with other studies summarised by Kelliher et al. (2014). All these results suggest that composition/activity of microbial communities regulating N transformations could be key drivers for differences in EF₃ between low and medium slopes, and future work to test this hypothesis is warranted.

4.3. Effect of slope on N₂O emission factors

In this study, there was no significant slope-effect for beef and dairy cattle urine or dung EF₃ values (Table 4), which are similar to those observed by Luo et al. (2015). There was a statistically significant difference between excreta-type (urine and dung) on both slope classes. EF₃ values for dairy and beef cattle urine were higher than those for dairy and beef cattle dung. These differences in EF₃ values between cattle urine and dung are not unexpected and are attributed to differences in N dynamics and transformations of urine-N and dung-N as explained above. These results are further supported by the meta-analysis of lowland and hill land urine and dung N₂O EF₃ data confirming that the EF₃ for animal urine was significantly higher than the corresponding EF₃ for dung (Kelliher et al. 2014). These differences in dung and urine EF₃ necessitated the use of disaggregated urine and dung EF₃ values in previous improvement in New Zealand N₂O inventory calculation (MfE 2016).

Our results support our hypothesis that N₂O EF₃ values for excretal inputs on established dairy hill land low and medium slopes or beef cattle grazing on low slopes would be similar due to improved soil fertility from intensified land use on these slopes despite being different to those reported for sheep- & beef-grazed hill-country pastures (Kelliher et al. 2014) where EF₃
values for low slopes or flatland were 65 to 75% higher than on medium slopes. The observed differences between the EF₃ values for the slopes obtained in the current study and those from previous studies appear to be caused by the grazing history of the experimental site. For example, the trials in the Northland, Waikato and Manawatu regions in the current study were located on dairy-grazed hill land pastures, while most of the previous hill country study sites were on hill country pasture grazed by sheep and beef. Previous study sites, where EF₃ values for dairy and beef cattle urine were lower on medium slopes than on low slopes, generally had low soil fertility (as indicated by the Olsen P status) due to low input and low grazing intensity on the medium slopes. However, the low slope and medium slope sites in the current study in the Northland, Waikato and Manawatu regions had been under intensive dairy management for many years. Accordingly, the soil fertility and nutrient cycling might have been like those on flatland dairy farms. It is, therefore, possible that EF₃ values for excreta of dairy cattle grazing on hill country land could be like those on flatland.

The differences in soil fertility levels observed between low and medium slopes at dairy grazed sites did not affect EF₃ values, indicating that the rates of N cycling on dairy grazed low and medium slope were similar. It is considered that despite the differences in background N₂O emissions of these dairy grazed low and medium slope sites under similar soil moisture conditions, the application of excreta-N elevated the concentrations of soil mineral N in the dung and urine treatments. The soil-plant rhizosphere responded by accelerating the N transformations and microbial and plant utilisation. But, the transformed mineral-N levels were probably surplus above the optimum to control N₂O emission and emissions did get elevated. These results indicate that despite the available N in control plots regulating background emissions, the abundance and diversity of microbial populations, built
up with intensive dairying N inputs, involved in N transformations were similar between slopes.

5. Implication of the findings

This study provided new data on N$_2$O fluxes and EF$_3$ values from dairy and beef cattle excreta on low (< 12°) and medium hill land slopes (12 - 25°) of sheep & beef cattle-grazed and dairy-grazed pastures. The methodology for estimating direct N$_2$O emissions from hill land sheep, beef, and deer grazed pastures in New Zealand by accounting for the effect of land slope on the N$_2$O EF$_3$ for urine and dung, proposed by Saggar et al. (2015), will assist in improving the accuracy of the national N$_2$O inventory. The EF$_3$ values from the present study and those summarised from previous studies (summarised by Kelliher et al. 2014) will make significant contributions to the refinement and completeness of the proposed new methodology for incorporation into New Zealand’s agricultural GHG inventory.

Our results show that EF$_3$ values for beef cattle urine (0.69%) or dung (0.19%) on medium slopes, when the excreta were applied on dairy-grazed hill land pastures were higher than those (0.32% and 0.06%) for cattle urine and dung, summarised in Kelliher et al. (2014), when the excreta were applied on beef- & sheep-grazed hill land pastures (Table 4). The EF$_3$ values for beef cattle urine (0.16%) or dung (0.05%) obtained in this study, when the excreta were applied on sheep & beef cattle-grazed hill land pasture (Otago site) are similar to those reported by Kelliher et al. (2014).

Overall, the current study not only confirms that dairy-grazed low-slope hill land would exhibit EF$_3$ values similar to those from previous New Zealand studies on beef-grazed low-slopes (Kelliher et al., 2014), but further suggests that EF$_3$ values for dairy urine or dung on medium
slopes on established dairy farms are similar to those found for low slopes. The extent to
which these differences in EF$_3$ influence the New Zealand N$_2$O emissions inventory has not
been estimated. Studies addressing this issue and conducting meta-analyses are the focus of
our current research.

In addition to the use of our measured country-specific variations in EF$_3$ in improving the
accuracy and transparency of farm-, regional- and national-scale N$_2$O inventories, these data
could also help farmers and policy-makers in devising strategies to reducing N$_2$O emissions by
efficiently targeting mitigation. The study suggests that the influence of grazing history and
hill land topography on soil fertility results in low-slopes being potential high N$_2$O emission
areas. It would be more efficient to focus mitigation strategies on those areas with high
emissions and EF$_3$ as opposed to a whole farm area blanket approach. Therefore, investment
in mitigation strategies to reduce N$_2$O emission will be better targeted where losses are
greatest and encouraging hill land livestock farming with animal species of low EF$_3$. Land-users
would be able to design their farm systems and farm environment plans in a more cost-
effective way.

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