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 (N_2O) emissions in New Zealand (NZ). N_2O emissions and emission factors (EF_3; percentage of excreta nitrogen emitted as N_2O) from sheep, beef- and dairy-cattle excreta deposited can vary with differences in the hill land slope and disaggregation of EF_3 based on slope may therefore result in a more accurate and improved inventory of national N_2O emission. However, research data on N_2O 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). N_2O 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 N_2O 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 EF_3 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 N_2O EF_3 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 EF_3 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 EF_3 to improve the accuracy and transparency of farm-, regional- and national-scale N_2O inventories. In addition, our findings could help farmers and policy-makers to devise strategies for reducing N_2O emissions, by targeting mitigation technologies to areas and sources with high EF_3.

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 (N_2O) produced by terrestrial ecosystems (Ussiri & Lal 2013). As a powerful GHG, N_2O has the global warming potential of 298 times of that of carbon dioxide (CO_2) and contributes to stratospheric ozone depletion (IPCC 2007, 2013). Livestock farming accounts for an estimated 2.1 Gt CO_2-eq of N_2O per annum, or 53 % of anthropogenic N_2O 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 N_2O from soils where their excreta is deposited (MfE 2016). Grazed pasture soils exhibit high potential for N_2O emissions from urine deposited by grazing livestock, and are

47 the primary source of direct and indirect N_2O emissions, contributing c. 64% of New Zealand's
48 8.59 Gg CO_{2e} agricultural N_2O emissions and 14.2% of emissions from agriculture sector (MfE
49 2018).

50 A series of studies focusing on measuring New Zealand specific N_2O emissions from sheep,
51 beef- and dairy-cattle excreta deposited on different topographies have been conducted (e.g.
52 van der Weerden et al. 2011; Hoogendoorn et al. 2013; Luo et al. 2013, 2016). Most of the
53 excreta N deposited onto grazed land is in the form of urea existing in the urine, while organic
54 N forms are deposited in the dung (Selbie et al. 2015; Chadwick et al. 2018). Hydrolysis of
55 urea and mineralisation of organic N to ammonium (NH_4^+) provide a pool of available nitrogen
56 (N) for the nitrification and denitrification processes, which are the main mechanisms for N_2O
57 production (Zhou et al. 2017). N_2O production is influenced by multiple factors, including
58 availability of N, soil aeration, pH and environmental conditions (Firestone & Davidson 1989;
59 Groffman & Tiedje 1991; Whalen et al. 2000; Xu et al. 2008). In grazed hill lands, slope
60 influences soil characteristics, pasture production, its N content and N uptake, excreta
61 deposition and environmental conditions such as soil bulk density, depth, moisture and
62 fertility (Saggar et al. 1990, 2015; Mackay et al. 1995; Luo et al. 2013). Research has shown
63 that N_2O emissions and emission factors (EF_3, percentage of deposited excreta N emitted as
64 N_2O) from steeper slopes are generally less than those from lower slopes and from flatland
65 (e.g. de Klein et al. 2009; Hoogendoorn et al. 2013; Luo et al. 2013, 2016; Saggar et al. 2015).
66 A meta-analysis also confirms that the EF_3 values for animal urine and dung deposited on
67 medium (12 - 25°) slopes are significantly lower than those from low (0 - 12°) slopes (Kelliher
68 et al. 2014).

69 The on-going intensification in dairying has, in some instances, lead to dairy cattle now grazing
70 hill country medium slopes. Disaggregation of EF_3 for urine and dung of different animals from
71 different slope levels can provide a more accurate inventory of national N_2O emission. Indeed,
72 the effect of land slope on the N_2O EF_3 for urine and dung on direct N_2O emissions from
73 excreta deposited by sheep, beef, and deer is likely to be incorporated into New Zealand's
74 national GHG inventory soon. However, there is no research data available on N_2O emissions
75 from dairy cattle grazing on low and medium slopes of hill country, while limited data exists
76 for beef cattle urine and dung on low slopes. Thus, the hill slope EF_3 values for dairy and beef
77 categories are less robust and leave a gap for adoption of the proposed changes to the
78 inventory methodology (Saggar et al., 2015). We hypothesize that N_2O EF_3 values for excretal
79 inputs on established dairy hill land low and medium slopes or beef cattle grazing on low
80 slopes would be similar due to improved soil fertility from intensified land use on these slopes.

81 The objectives of this study were to: i) determine N_2O emissions and EF_3 values from dairy
82 and beef cattle urine and dung on low (< 12^o) and medium hill land slopes (12 - 25^o) of sheep
83 & beef cattle-grazed and dairy-grazed pastures; and ii) contribute to the refinement and
84 completeness of the proposed new methodology (Saggar et al. 2015) for incorporation into
85 New Zealand's agricultural GHG inventory.

86

87 **2. Materials and methods**

88 2.1. Site and soil description

89 Four trial sites were selected across the range of climatic conditions in Northland, Waikato,
90 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^{o}) and medium (12^{o} - 25^{o}) 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 N_2O measurements. These were used for destructive soil sampling. Real excreta were applied for N_2O 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/m^2. On medium slope areas, the urine application rate was 6.7 L/m^2 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/m^2 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 N_2O emissions, and the methodology was based on that used the previous published studies on excreta N_2O emissions (de Klein et al.

2003; Saggar et al. 2004; Luo et al. 2015). 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 N_2O flux between the plots and to assist with interpretation of patterns of N_2O 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 N_2O flux values and soil mineral N content for treatment plots reached the background levels measured in the control plots. During weekly phases of N_2O 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, N_2O 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 t_0, t_{30} and t_{60} (or similar) for the first nine gas sampling occasions and during a cover period of 45 minutes (or similar) at times t_0 and t_{45} 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 ^{o}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 N_2O concentration within the chamber headspace, for the gas samples collected at t_0, t_{30} and t_{60} were generally linear (R^2 >0.90). Therefore, the hourly N_2O fluxes were calculated (Mosier & Mack, 1980) using liner regression and the ideal gas law according to Equation 1:

160 $$F = \frac{\delta N_2O}{\delta T} \times \frac{M}{V_m} \times H \quad (1)$$

161 where, F is the hourly N_2O fluxes (mg N m^{-2} h^{-1}); δN_2O is the increase in head space N_2O over
162 time (μL L^{-1}); δT is the enclosure period (hours); M is the molar weight of N in N_2O; V_m is the
163 molar volume of gas at the sampling temperature (L mol^{-1}); H is the height of headspace (m).

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

167 $$EF_3 = \frac{N_2O_{excreta} - N_2O_{control}}{excreta\ N\ applied} \times 100\% \quad (2)$$

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

172

173 2.6. Soil and climatic parameters

174 At the start of each trial, a bulk soil sample comprising 12 soil cores was collected from each
175 trial site for soil chemical analysis, including pH, Olsen P, total Kjeldahl N and organic carbon,
176 while at least 10 other intact cores from each site were collected for soil bulk density
177 determination. The soil chemical and physical properties are shown in Table 1. In general, Olsen
178 P, organic matter and total N were high in soil on low slopes compared to medium slopes in
179 each of the four regions. The Northland low slope area had a very high Olsen P level at 66 μg
180 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^{o}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_2O fluxes, measured just before treatment application, were generally higher in the low-slope areas than in the medium areas, with the highest baseline N_2O flux being at 2.18 mg N m^{-2} d^{-1} on the Northland low slope and the least baseline N_2O 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_2O emissions from the measured areas that had no excreta applied (i.e. the control treatments) were about 1.28 and 0.17 kg N_2O-N ha^{-1} over the 4 to 6 months (winter/early-

225 spring) measurement period for the low and medium slopes, respectively (Fig. 4). The highest
226 emission value (4.03 kg N_2O-N ha^{-1}) was found at the Northland site, while the lowest
227 emissions (0.02 kg N_2O-N ha^{-1}) were found from the medium-slope area at the Otago site.

228

229 3.2.2. Nitrous oxide emissions from urine and dung

230 Application of either urine or dung increased N_2O fluxes, but the patterns and magnitudes of
231 the increases were not consistent between excreta types, slope classes or regions (Fig. 3). The
232 largest increase in N_2O flux was from dairy cattle urine on the low slope in the Northland site
233 (432 mg N m^{-2} d^{-1}) and the smallest increases in the Otago site, with higher N_2O fluxes being
234 generally observed on low slopes than on medium slopes in all regions. N_2O fluxes from dairy
235 or beef cattle dung were generally low at both low and medium slopes at all four sites (Fig.
236 3). Total N_2O emissions from dairy urine were 3.0 -11.5 kg N_2O-N ha^{-1} in Northland, 2.0 to 8.9
237 kg N_2O-N ha^{-1} in Manawatu, 0.67-1.07 kg N_2O-N ha^{-1} in Waikato, and 0.3-2.7 kg N_2O-N ha^{-1} in
238 Otago. Similar magnitudes of the total N_2O emissions were also found from beef cattle urine
239 in the respective regions.

240

241 3.3. Soil mineral-N and moisture conditions

242 Soil concentrations of NH_4^+-N and NO_3^--N in the control treatments were generally low for
243 both slope areas in all four trial sites throughout the sampling period (<20 mg N kg^{-1} dry soil)
244 due to there being no extra mineral N input in control treatments (Fig. 3). Concentrations of
245 NH_4^+-N in the soil peaked either on the day of urine application or within several days after
246 urine application. Nitrification of urine N was rapid at the Northland and Waikato sites, as soil
247 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

271 medium slope (0.229%). The sites in Northland and Manawatu region produced the higher
272 EF_3 values than the sites in Waikato and Otago regions (Table S1). Effects on EF_3 by slopes,
273 animal species and excreta types are presented in Table 3. The probabilities of a slope class
274 animal species (P = 0.656), slope class × excreta type and slope class × animal species effects
275 including slope class x animal species × excreta type were non-significant.

276 Analysis of the urine and dung EF_3 data (Table 4) showed different slope effects from the
277 dairy-grazed hill land farms (Northland, Waikato and Manawatu) than those from the sheep
278 & beef cattle-grazed hill farm (Otago). The EF_3 values were lower on medium slope (0.048-
279 0.157%) than on low slope (0.183-0.573%) for the sheep & beef cattle -grazed Otago site, with
280 no significant difference in EF_3 between low slope and medium slope for the dairy-grazed
281 pastures. When the combined EF_3 data from all 4 regions were analysed, there was a trend
282 for lower EF_3 for each excreta type on the medium slope (0.143-0.526%) than on the low slope
283 (0.162-0.708%) (Table 4). However, the analysis indicates that the slope class effect was not
284 statistically significant.

285

286 **4. Discussion**

287 4.1. Nitrous oxide emissions from cattle excreta on hill land

288 The current default New Zealand IPCC EF_3 values are 1% and 0.25% for animal urine and dung,
289 respectively (MfE, 2016). The average EF_3 values obtained over the measurement periods for
290 the four regions in this study (Table 4) are lower than these default annual EF_3 values. Rainfall
291 and soil drainage conditions affect soil WFPS and oxygen diffusivity, consequently influencing
292 microbe's activity and regulating the N_2O emissions (Dobbie & Smith 2001; Saggar et al. 2004;
293 Eva et al., 2015; Lark & Milne 2017). Lower N_2O 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_2O 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 ($R = 0.32$, $P > 0.05$, $n = 16$).

318 A significant and positive relationship observed in this study between soil Olsen P levels and
319 the EF_3 data for cattle urine (R = 0.42, n = 16) is similar to that reported for sheep urine was
320 in previous hill land field trials (Luo et al. 2013). Olsen P, as an indicator for soil fertility status
321 in legume-based New Zealand pastures (Tillman et al. 2012), might be associated with labile
322 N and C, and abundance and activity of soil microbes, which regulate excreta-induced N_2O
323 emissions and background emissions (Hoogendoorn et al. 2013; Jha et al. 2017). However, the
324 absence of a significant relationship between soil Olsen P on background emissions and cattle
325 dung EF_3 could be due to the low emission factors found for cattle dung (Table S1). It may also
326 be related to microorganisms, C and nutrients contained in deposited dung itself that could
327 regulate N_2O emissions to some extent.

328 Application of animal excreta has been reported to stimulate N transformation reactions and
329 increase N_2O emissions (van Groenigen et al. 2005; van der Weerden et al. 2011;
330 Hoogendoorn et al. 2013; Luo et al. 2013, 2015, 2016; Sordi et al. 2014; Chadwick et al. 2018).
331 In this study, N_2O fluxes also generally increased following excreta deposition, with the
332 magnitude of the increase being greater from both dairy and beef urine application than from
333 dung application (Figs. 3; 4). Compared to dung application, urine could rapidly supply
334 available mineral N for nitrification and denitrification through hydrolysis of the urea, leading
335 to higher N_2O emissions (Todd & Hausinger 1989; Kaminskaia & Kostic 1997; Udert et al. 2003;
336 Hristov et al. 2011). However, N_2O fluxes remained elevated for longer periods for the dung
337 treatments than for the urine treatments in most regions (Fig. 3), probably due to slow
338 formation of mineral N from decomposition of organic matter in dung (Horton et al. 1992;
339 Zhang et al. 2007; Vavilin et al. 2008; Hristov et al. 2011).

340 The increased N_2O fluxes generally coincided with increased soil NH_4^+-N and NO_3^--N
341 concentrations measured after excreta application (Fig. 3); however, N_2O fluxes and soil
342 mineral N content measured over the course of the experiments were not significantly
343 correlated ($P > 0.05$). It is likely that most of the applied excreta N may have been taken up
344 by plants, immobilised into the soil, leached out from the surface soil layers or lost to the
345 atmosphere through ammonia volatilisation. This would consequently have reduced the
346 amount of mineral N available for denitrification and N_2O production. N_2O fluxes are also
347 regulated by soil WFPS (Luo et al. 2013). Soil WFPS is affected by rainfall and accordingly, the
348 high N_2O fluxes observed in this study generally coincided with rainfall events (Figs. 2; 3).

349

350 4.2 Effect of management history on EF_3

351 The differences in the background N_2O fluxes between the medium and the low slope sites,
352 measured before treatment application may reflect differences in soil fertility status resulting
353 from variable nutrient inputs caused by intensification of livestock farming at the sites (Table
354 1). The basic soil properties (Olsen P and OC) accounted for these, with the correlation
355 coefficients (r) between background N_2O fluxes and Olsen P and OC (0.96, 0.46 and 0.51,
356 respectively). Soils with high fertility indicators (Olsen P and OC) generally indicate greater
357 abundance and activity of soil microbes and potentially lead to higher level of mineralised N
358 contributing to high N_2O fluxes (Tillman et al. 2012).

359 The hill country soil used in the Otago region had lower fertility compared to the soils in the
360 other three regions (Table 1), which is likely to have resulted in the observed lower EF_3 (Table
361 4 and S1). The Otago site had been under a sheep & beef grazing management regime. Higher
362 EF_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 EF_3. 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 EF_3 between low and medium slopes, and future work to test this hypothesis is warranted.

4.3. Effect of slope on N_2O emission factors

In this study, there was no significant slope-effect for beef and dairy cattle urine or dung EF_3 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. EF_3 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 N_2O EF_3 data confirming that the EF_3 for animal urine was significantly higher than the corresponding EF_3 for dung (Kelliher et al. 2014). These differences in dung and urine EF_3 necessitated the use of disaggregated urine and dung EF_3 values in previous improvement in New Zealand N_2O inventory calculation (MfE 2016).

Our results support our hypothesis that N_2O EF_3 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 EF_3

386 values for low slopes or flatland were 65 to 75% higher than on medium slopes. The observed
387 differences between the EF_3 values for the slopes obtained in the current study and those
388 from previous studies appear to be caused by the grazing history of the experimental site. For
389 example, the trials in the Northland, Waikato and Manawatu regions in the current study
390 were located on dairy-grazed hill land pastures, while most of the previous hill country study
391 sites were on hill country pasture grazed by sheep and beef. Previous study sites, where EF_3
392 values for dairy and beef cattle urine were lower on medium slopes than on low slopes,
393 generally had low soil fertility (as indicated by the Olsen P status) due to low input and low
394 grazing intensity on the medium slopes. However, the low slope and medium slope sites in
395 the current study in the Northland, Waikato and Manawatu regions had been under intensive
396 dairy management for many years. Accordingly, the soil fertility and nutrient cycling might
397 have been like those on flatland dairy farms. It is, therefore, possible that EF_3 values for
398 excreta of dairy cattle grazing on hill country land could be like those on flatland.

399 The differences in soil fertility levels observed between low and medium slopes at dairy
400 grazed sites did not affect EF_3 values, indicating that the rates of N cycling on dairy grazed
401 low and medium slope were similar. It is considered that despite the differences in
402 background N_2O emissions of these dairy grazed low and medium slope sites under similar
403 soil moisture conditions, the application of excreta-N elevated the concentrations of soil
404 mineral N in the dung and urine treatments. The soil-plant rhizosphere responded by
405 accelerating the N transformations and microbial and plant utilisation. But, the transformed
406 mineral-N levels were probably surplus above the optimum to control N_2O emission and
407 emissions did get elevated. These results indicate that despite the available N in control plots
408 regulating background emissions, the abundance and diversity of microbial populations, built

409 up with intensive dairying N inputs, involved in N transformations were similar between
410 slopes.

411

412 **5. Implication of the findings**

413 This study provided new data on N_2O fluxes and EF_3 values from dairy and beef cattle excreta
414 on low (< 12^o) and medium hill land slopes (12 - 25^o) of sheep & beef cattle-grazed and dairy-
415 grazed pastures. The methodology for estimating direct N_2O emissions from hill land sheep,
416 beef, and deer grazed pastures in New Zealand by accounting for the effect of land slope on
417 the N_2O EF_3 for urine and dung, proposed by Saggar et al. (2015), will assist in improving the
418 accuracy of the national N_2O inventory. The EF_3 values from the present study and those
419 summarised from previous studies (summarised by Kelliher et al. 2014) will make significant
420 contributions to the refinement and completeness of the proposed new methodology for
421 incorporation into New Zealand's agricultural GHG inventory.

422 Our results show that EF_3 values for beef cattle urine (0.69%) or dung (0.19%) on medium
423 slopes, when the excreta were applied on dairy-grazed hill land pastures were higher than
424 those (0.32% and 0.06%) for cattle urine and dung, summarised in Kelliher et al. (2014), when
425 the excreta were applied on beef- & sheep-grazed hill land pastures (Table 4). The EF_3 values
426 for beef cattle urine (0.16%) or dung (0.05%) obtained in this study, when the excreta were
427 applied on sheep & beef cattle-grazed hill land pasture (Otago site) are similar to those
428 reported by Kelliher et al. (2014).

429 Overall, the current study not only confirms that dairy-grazed low-slope hill land would exhibit
430 EF_3 values similar to those from previous New Zealand studies on beef-grazed low-slopes
431 (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_2O 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_2O inventories, these data could also help farmers and policy-makers in devising strategies to reducing N_2O 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_2O 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_2O 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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457

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