Determination of factors affecting upscaling of nitrous oxide emissions in hill country

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Executive summary

In our current N_2O inventory methodology, the N_2O emissions from hill country are estimated in the same way as N_2O emissions from dairy grazed flat land (i.e. multiplying the estimated amount of nitrogen (N) excreted with a constant emission factor (EF_3); EF_3 = 1%). However, N_2O emissions from hill land are much more spatially variable than those in flat land, largely due to the topography-driven spatial variability of the drivers of these emissions.

The purpose of this study was to provide:

- A framework for estimating and up-scaling N_2O emissions from hill country farms, based on current understanding of the key factors affecting the spatial variability in N_2O emissions and utilising existing spatial databases of land, soil and animal classes/density in NZ hill country.
- Recommendations for the most effective field campaigns to be conducted to determine EF_3 in key Hill country Land Units (HLU) in NZ.

Hill land was disaggregated into 18 HLUs based on soil drainage class (free, imperfectly and poorly), aspect (NW and SE) and slope (low, medium and high), and total N_2O emissions were estimated as a product of a) the total area of land in each HLU, b) the N excretion rate in each HLU, and c) the EF_3 assigned to that HLU:

$$N_2O_{\text{Hill country}} = \sum_i (HLU_i \bullet Nreturn_i \bullet EF_{3i})$$

Where,

HLU*i* = Area of land in Hill country Land Unit *i*, as defined by slope, aspect, and drainage class; *i* = 1, …n. (ha)

Nreturn *i* = amount of excreta N deposited in HLU *i* (kg N excreted/ha)

EF_3 *i* = N_2O emission factor for N deposited in HLU *i* (kg N_2O-N/kg N excreted)

For each region in New Zealand the total area of land within each HLU were estimated using spatial soil and land-use data bases (LENZ, NZLRI, 25-m DEM). Regional animal numbers were estimated using the Agribase data-base and these were equally apportioned between flat land and hill land for each region. The total amount of N excreted in each HLU was then estimated using an average N excretion rate per animal (Clark et al 2003) and a nutrient transfer model (Saggar et al, 1990a, b).

Hill Land Units were then categorised into 5 different emission factors classes (very high, high, medium, low and very low) – based on existing knowledge of N_2O emission factors and of the drivers of emissions – and N_2O emissions were estimated for a range of emission factor-scenarios:

Scenario 1	EF_3 set at 1 % for all HLUs as in NZ Inventory
Scenario II	a relatively high EF_3 for all HLUs
Scenario III	a moderate/reasonable EF_3 for all HLUs
Scenario IV	a slightly lower than moderate/reasonable EF_3 for all HLUs
Scenario V	fairly low EF_3 for all HLUs
Scenario VI	a very high EF_3 for HLUs that are expected to have high emissions, and a very low EF_3 for HLUs that are expected to have low emissions

The results indicated that, independent of the emission factor-scenario chosen, low slope areas (camp sites) on free draining soils made a largest contribution to national N_2O emissions. This was due to the large prevalence of free draining soils compared to imperfectly or poorly draining soils (79, 18 and 2% of hill land respectively), as well as the relatively large amount of N excreted in low slope areas compared to medium and high slopes (57, 31 and 12% of total N excreted respectively). In addition, the majority of HLUs with low slope areas were in the 'high' or 'very high' emission factor categories.

The results also highlighted that the relative contribution of NW or SE aspects to N_2O emissions were generally even and ranged between 40-60%. However, the current assumption was that NW aspects have higher emission factors due to animal preference for these warmer/sunnier aspects resulting in more compaction and higher fertility. On the other hand, these aspects are likely to have lower soil moisture contents than the SE aspects, which could result in lower emission factors. The current assumption that EF_3 on NW aspect are high needs to be tested to ensure our current estimates are not overestimating N_2O emissions of these areas.

Apart from the choice of emission factors, our current estimates are also heavily dependent on the estimated area of land and stock numbers within each HLU, as well as on the relative proportioning of the excreted N between slope and aspect classes. Further work is recommended to refine the estimates of land area and stock numbers and to test the nutrient transfer model for apportioning N between slope and aspect classes in a wider range of hill land systems. In addition, we also recommend testing our framework in one or two representative districts/regions for which good spatial data is available. This will reduce some of the uncertainty around the animal numbers, the areas of land within each HLU and N excreta distribution, and will confirm the key HLUs that contribute most to overall N_2O.

Although estimating total N_2O emissions from hill country was not a primary aim of the current project, all the scenarios tested here suggest a potential for a reduction in New Zealand's GHG inventory when EF_3 values for hill land are disaggregated based on the proposed framework.

In summary, while acknowledging the constraints and limitations of the current study, the current study provides a useful framework for estimating and up-scaling N_2O emissions from hill country farms, and highlights the HLUs that are likely to make the largest contribution to the N_2O emissions. Recommendations for further research are provided and include:

a. Test the current framework in key regions with good spatial data
b. Refinement of EF_3 in low slope areas (especially on free draining soils)
c. Determining the effect of aspect on EF_3
d. Refine estimates of land area and stock numbers
e. Validating the nutrient transfer model for a wider range of hill land systems

1. Introduction

Direct and indirect nitrous oxide (N_2O) emissions from animal excreta deposited during grazing contribute over 80% of the total agricultural N_2O emissions in NZ.

Grazed hill country comprises 60% of the total farmed area of land in New Zealand (Statistics New Zealand, 2003) with 25% of the national sheep flock and 20% of the beef cattle herd occupying hill country in the North Island. In our current N_2O inventory methodology, the N_2O emissions from hill country are estimated in the same way as N_2O emissions from dairy grazed flat land (i.e. multiplying the estimated amount of nitrogen (N) excreted with a constant emission factor (EF_3); EF_3 = 1%). However, previous work has suggested that EF_3 from sheep or cattle urine patches in hill country are likely to be lower than 1% (Carran and Saggar 2004; de Klein *et al*. 2004; Hoogendoorn *et al.* 2008), due to i) differences in the size and frequency of urination events between sheep and dairy cattle; ii) lower soil fertility, and lower soil substrate N and soluble carbon (C) availability due to lower stocking intensity in hill country compared to dairy grazed flat land; iii) increased spatial variability in excreta N return in hill country; and/or iv) more pronounced spatial variability in soil parameters known to drive N_2O emissions (e.g. soil moisture, temperature, mineral N and soluble C) due to spatial differences in topography and aspect that are typical for NZ hill country. Detailed seasonal field campaigns to refine EF_3 for hill country, such as conducted between 2000 and 2004 to refine EF_3 for cow urine on flat land, need to encompass this increased spatial variability and could therefore be very costly. This project will provide recommendations for the most effective field campaigns to be conducted to determine EF_3 in hill country by developing a framework for estimating and up-scaling N_2O emissions from hill country farms based on our current understanding of driving variables of N_2O emissions, existing spatial databases of slope, aspect, soil type, soil fertility status and/or any other relevant factors, and estimates of a spatial distribution of excretal N.

Our hypothesis is that N_2O emissions from hill country can be satisfactorily up-scaled as follows:

$$N_2O_{\text{Hill country}} = \sum_i (HLU_i \bullet Nreturn_i \bullet EF_{3i})$$

Where,

HLU*i* = Hill country Land Unit *i*, as defined by slope, aspect, soil type, fertility status and/or any other relevant factors; *i* = 1, …n.

Nreturn *i* = amount of excreta N deposited in HLU *i*

EF_3 *i* = N_2O emission factor for N deposited in HLU *i*

2. Objectives

The objectives of this study are to

- Define Hill country Land Units (HLU) based on a review of the driving variables of N_2O emissions,
- Spatially map HLUs and animal stocking numbers
- Estimate excreta N deposition rates for each HLU,
- Estimate the relative contribution of each HLU to total N_2O emissions in hill country

3. Outcome

The outcomes of the study are to provide:

- A framework for estimating and up-scaling N_2O emissions from hill country farms, based on current understanding of the key factors affecting the spatial variability in N_2O emissions and utilising existing spatial databases of land, soil and animal classes/density in NZ hill country.
- Recommendations for the most effective field campaigns to be conducted to determine EF_3 in key Hill country Land Units (HLU) in NZ.

4. Materials and methods

4.1 Defining hill country and hill land units (HLUs)

For the purpose of this project we defined hill country as land areas which have a slope predominantly greater than 12°, are below the tree line, and which are grazed by sheep and/or beef cattle. Areas of land held by the conservation estate and in QEII Trust were excluded. These defined hill country areas were then disaggregated into Hill Land Units (HLUs) based on broad categories of 3 soil drainage classes, 2 aspect categories and 3 slope classes. This information is generally available throughout all geographical areas in New Zealand.

4.2 Spatially map HLUs and animal stocking numbers

The methodology of defining HLUs involved defining hill country from a number of spatial analysis rule parameters. Calculating HLUs included using a number of spatial data bases and topographical layers. These were slope, aspect and drainage using the Land Environments of New Zealand (LENZ) drainage layer, Land Cover Database 2 (LCDB2), a spatial data layer showing areas above and below tree line, and protected areas from the Protected Areas Network Database (PAN-NZ). Slope and aspect data layers were derived from a high resolution 25-m digital elevation model (DEM) of New Zealand (Barringer *et al.* 2004). The LENZ drainage layer was based on data from the New Zealand Land Resource Inventory (NZLRI). Predominately these calculations were made using 25-m resolution grid layers using ArcGIS 9.2 software with Spatial Analyst extensions.

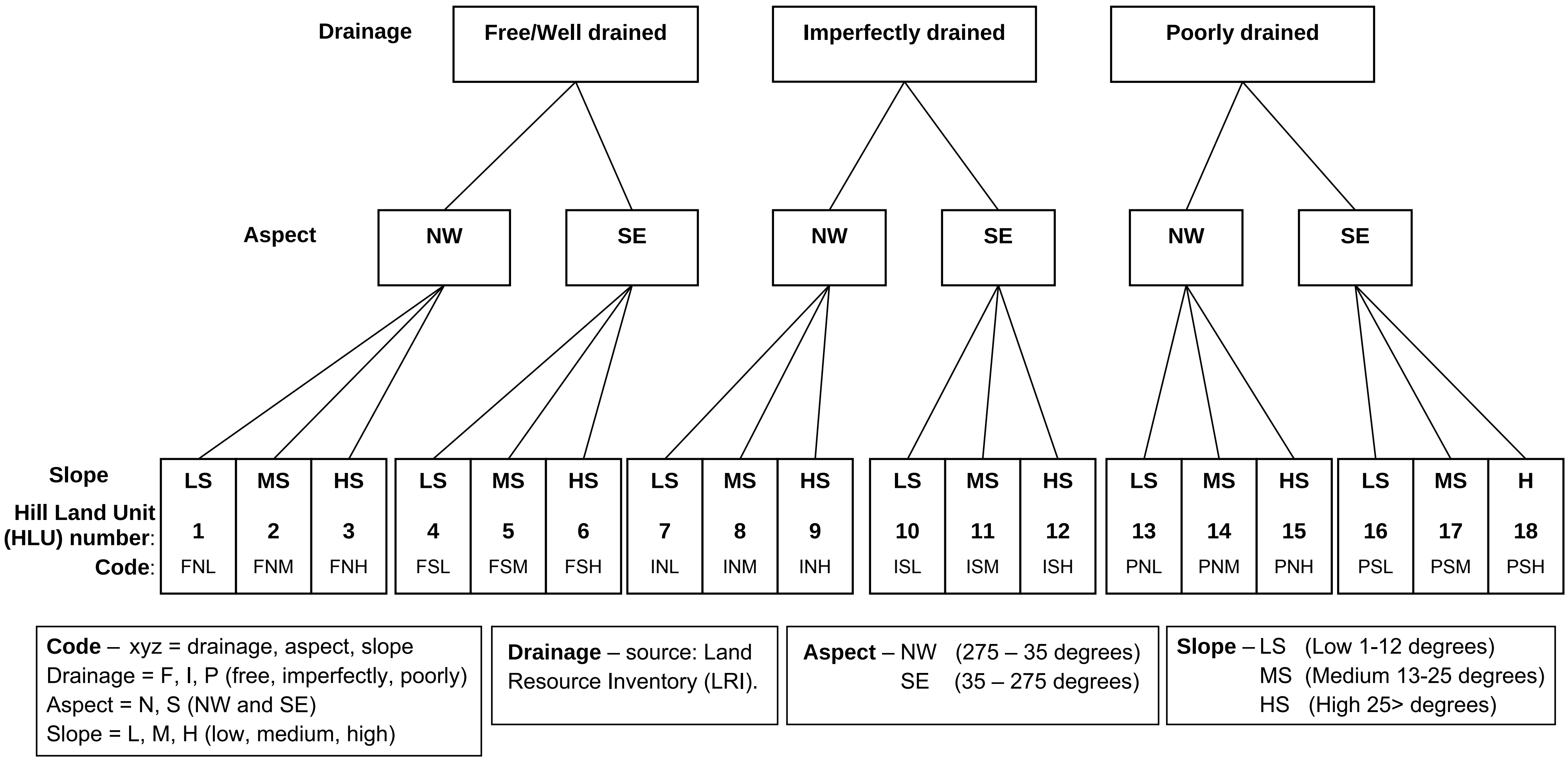
The first part of the methodology process involved calculating hill land throughout New Zealand. This was derived using the following decision rules:

- Slope >12 degrees (25-m DEM).
- Land cover database land classes 40 and 41, i.e. high producing exotic grassland, and low producing exotic grassland (LCDB2).
- Areas within the tree-line.
- Areas not included in protected areas e.g. DoC conservation estate, QEII Covenants, Regional Parks, and Nga Whenua Rahui land (2007 PAN-NZ version).

Within this hill land, HLUs were defined (Figure 1) and the total area of land for each HLU was estimated using additional spatial data layers including aspect, the LENZ drainage layer, and further analysis of the 25-m resolution slope layer. The following decision rules to define HLU included:

- 3 soil drainage classes: poorly, imperfectly and freely draining soil, based on the five drainage class descriptors in the LENZ/NZLRI database as follows: poorly = class 1 (‘very poorly’) and 2 (‘poorly’); imperfectly = class 3 (‘imperfectly’); freely = class 4 (‘moderately well’) and 5 (‘well drained’).
- 2 aspect categories: northeast (NE: 275 – 35 degrees) and southwest (SW: 35 – 275 degrees)
- 3 slope classes: Low slope (LS: 1-12 degrees); Medium slope (MS: 12-25 degrees); High slope (HS: >25 degrees)

Figure 1: Schematic description of the Hill Land Units



4.3 Estimating stock numbers and N excretion rates

Estimates of the amount of excreta N deposited per annum to each HLU within each region were derived from total stock numbers grazing in each HLU and amounts of N excreted per animal using the following approaches.

a) The total number of stock grazing in each hill land region was calculated by taking:

   i. Total stock numbers obtained from the AgriBase Data Base.

   ii. The spatial information of the AgriBase Data Base farms was then intersected with the 'hill land' areas per region to obtain total stock numbers in the areas which were defined in this study as hill land.

   It was not possible to compare the stock number data from the AgriBase Data Base with that of the national inventory because of discrepancies between comparing information from a spatial data set and a non spatial data set such as that used for the New Zealand inventory.

b) The N excretion rates per HLU (kg excretal N deposited/ha per year) was estimated by using the total number of animals grazing in hill country calculated in (a) above and :

   i. The amount of N excreted per animal was calculated using the approach of Clark *et al*. (2003) in accordance with the New Zealand inventory.

   ii. A nutrient transfer model (NTM) developed by Saggar *et al*. (1990a, b) (Appendix 1). This model calculates the proportional distribution of excretal N for each HLU.

4.4 Estimating the relative contribution of each HLU to total N_2O emissions from hill country

A relative emission factor (EF_3) was assigned to each HLU based on existing knowledge of the drivers of N_2O emissions and on the values attained for EF_3 in field trials, albeit predominantly from flat land areas (Appendix 2) (Table 1).

Table 1 Schematic diagram of Hill Land Units (HLUs) with relative EF_3 categories assigned.

Freely /Well drained soil						Imperfectly drained soil						Poorly drained soil						Drainage Class
NW[1]			SE			NW			SE			NW			SE			Aspect[1]
LS[2]	MS	HS	LS	MS	HS	LS	MS	HS	LS	MS	HS	LS	MS	HS	LS	MS	HS	Slope[2]
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	HLU no.
FNL	FNM	FNH	FSL	FSM	FSH	INL	INM	INH	ISL	ISM	ISH	PNL	PNM	PNH	PSL	PSM	PSH	HLU code[3]

[1]Aspect: **NW** = northwest aspect (275 – 35 °; **SE** = (35 – 275 °)

[2]Slope: **LS** = low slope of 0-12°; **MS** = medium slope of 13-25°; **HS** = high slope of >25°

[3]HLU code: **XYZ** = drainage, aspect, slope; Drainage = F, I, P (free, imperfectly, poorly); Aspect = N, S (NW and SE); Slope = L, M, H (low, medium, high)

Where:

Very high EF_3 = **HLUs 13 and 16 (PNL and PSL)**

High EF_3 = **HLUs 1, 7 and 14 (FNL, INL and PNM)**

Moderate EF_3 = **HLUs 8, 10 and 17 (INM, ISL and PSM)**

Low EF_3 = **HLUs 2, 4, 11, 15 and 18 (FNM, FSL, ISM, PNH and PSH)**

Very low EF_3 = **HLUs 3, 5, 6, 9 and 12 (FNH, FSM, FSH, INH and ISH)**

To assign the EF_3 values, the following relativities were used:

A very high EF_3 is likely on poorly drained soils of LS and on a NW and SE aspect (high likelihood of being moist, having a high concentration of N and C substrate). This would include HLUs **13** and **16**.

A high EF_3 is likely to be present on poorly drained soils of MS and NW aspect, on imperfectly drained soils of LS and NW aspect, and on freely draining soils of LS and NE aspect. This would include HLUs **1**, **7** and **14**.

A moderate $EF3_3$ is likely to be found on poorly drained soils of MS and SE aspect, on imperfectly drained soils of LS and SE aspect and on imperfectly drained soils of MS and NW aspect. This would include HLUs **8**, **10** and **17**.

A low EF_3 is likely to be found on HS areas of poorly drained soils on both NW and SE aspects, on imperfectly drained soils of MS and SE aspect and on freely drained soils of MS on NW aspect and on LS and SE aspects. This would include HLUs **2**, **4**, **11**, **15**, and **18**.

A very low EF_3 would be expected from imperfectly drained soils of HS on both NW and SE aspects, and on freely drained soils of HS and NW aspect and those of MS and HS of SE aspect. This would include HLUs **3**, **5**, **6**, **9**, and **12**.

Considering the large spatial and temporal variability in N_2O emissions and data from previous New Zealand studies (appendix 2) a range of emission factors were used to construct five plausible emission factor scenarios (Scenarios II - VI) (Table 2).
Where:

Scenario 1 = EF_3 set at 1 % for all HLUs as in NZ Inventory
Scenario II = a relatively high EF_3 for all HLUs
Scenario III = a moderate/reasonable EF_3 for all HLUs
Scenario IV = a slightly lower than moderate/reasonable EF_3 for all HLUs
Scenario V = fairly low EF_3 for all HLUs
Scenario VI = a very high EF_3 for HLUs that are expected to have high emissions, and a very low EF_3 for HLUs that are expected to have low emissions

The total amount of N_2O emitted under each of these 5 scenarios was then compared to that emitted under Scenario I which is the currently used approach in the NZ inventory where EF_3 = 1% for all 18 defined HLUs.

Table 2 Emission factors assigned to each of the 18 HLUs under 6 different scenarios

		Assigned emission factors (EF_3) (%)					
Relative Emissions	**HLUs**	**Scenario I[1]**	**Scenario II[2]**	**Scenario III[3]**	**Scenario IV[4]**	**Scenario V[5]**	**Scenario VI[6]**
Very high	13, 16	1.00	2.00	1.50	1.00	0.50	2.50
High	1, 7, 14	1.00	1.50	1.00	0.75	0.25	1.00
Moderate	8, 10, 17	1.00	1.00	0.60	0.50	0.10	0.20
Low	2, 4, 11, 15, 18	1.00	0.50	0.30	0.25	0.05	0.05
Very Low	3, 5, 6, 9, 12	1.00	0.05	0.05	0.05	0.01	0.001

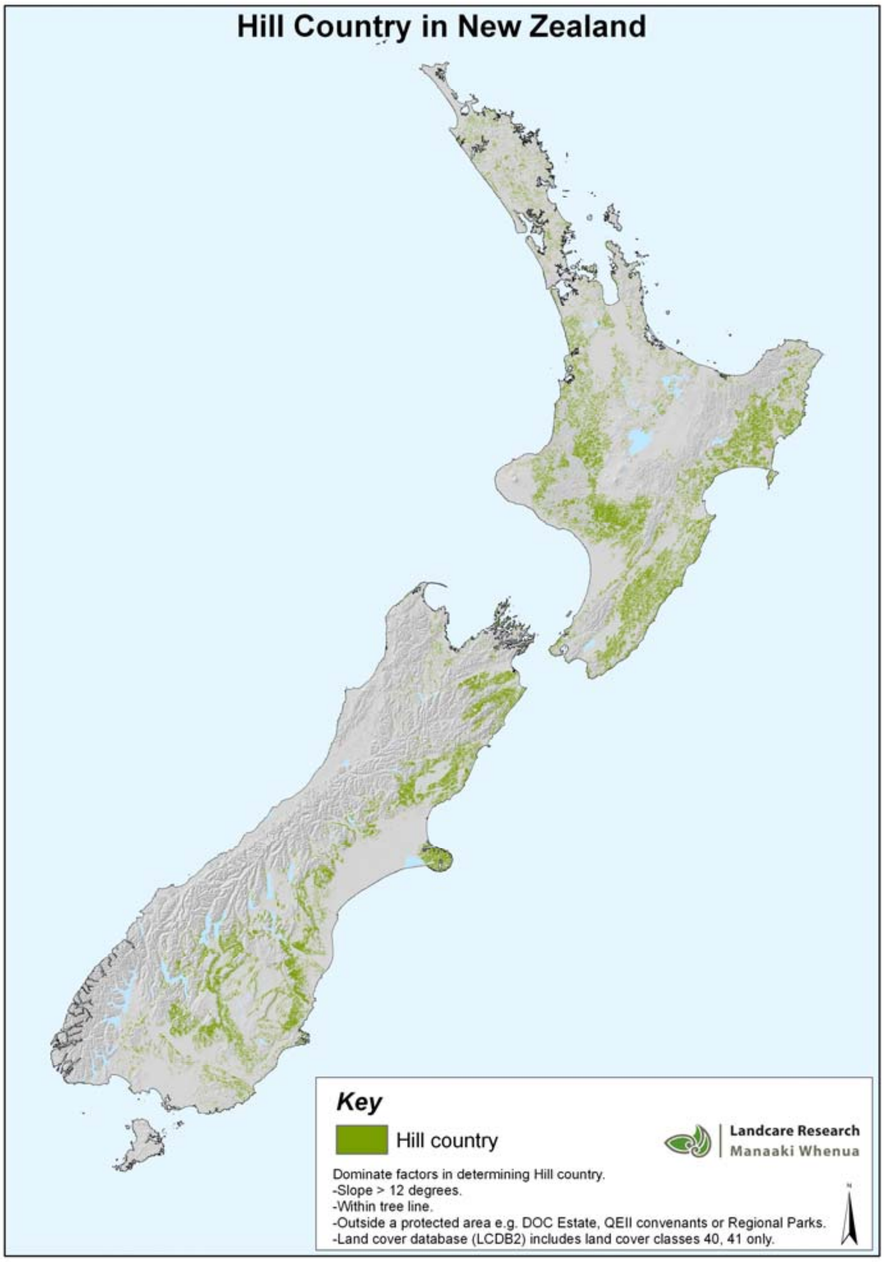
[1]Scenario 1 = EF_3 set at 1 % for all HLUs as in NZ Inventory
[2]Scenario II = a relatively high EF_3 for all HLUs
[3]Scenario III = a moderate/reasonable EF_3 for all HLUs
[4]Scenario IV = a slightly less than moderate/reasonable EF_3 for all HLUs
[5]Scenario V = fairly low EF_3 for all HLUs
[6]Scenario VI = a very high EF_3 for HLUs that are expected to have high emissions, and a very low EF_3 for HLUs that are expected to have low emissions

5. Results

5.1 Defining hill country land units (HLUs)

The specific criteria chosen to describe hill land for the purpose of this study (section 4.1) resulted in a total of 2.91 million ha being identified as hill land. These areas are illustrated in Figure 2 below. There are some discrepancies with respect to both total and by region area in hill country between the AgriBase database and the Meat & Wool Economic Service data and these could not be resolved within the timeframe and the funding for this project. In this study very specific criteria were used to define hill land such as: Slope >12 degrees (25-m DEM), Land cover database land classes 40 and 41, i.e. high producing exotic grassland, and low producing exotic grassland (LCDB2), areas within the tree-line and excluded protected areas e.g. DoC conservation estate, QEII Covenants, Regional Parks, and Nga Whenua Rahui land (2007 PAN-NZ version). Hill country as defined by the Meat & Wool Economic Service data is more extensive and includes 8 classes of farm land based on Farm Class Survey. However the Meat & Wool Economic Service data does not specify the areal distribution of these farms and could therefore not be used for the current project.

Figure 2: Map of NZ hill land



Our estimates show that this hill land supports 10 million sheep (~25% of total New Zealand sheep) and 1.24 million beef cattle (~28% of New Zealand beef cattle) (Table 3). No diary grazed land was included in our defined hill land. Half of this hill land is situated in 3 of the 16 regions (Canterbury, Manawatu-Wanganui, Otago) which support 60% of total sheep numbers in hill land.

Table 3 Total area of land and number of sheep and beef within each region

Region	Hill Land (ha)	Sheep Numbers	Beef Numbers
Northland	103511	73995	267651
Auckland	37571	65650	142778
Waikato	235244	304158	190187
Bay of Plenty	38127	123698	50151
Gisborne	217906	214952	43684
Hawkes Bay	256702	514827	91232
Taranaki	82196	180342	31794
Manawatu-Wanganui	505311	1250950	133993
Wellington	142819	634657	36829
West Coast	2073	7203	6279
Canterbury	533504	1693020	94447
Otago	451354	2919784	70304
Southland	126730	1711928	33561
Tasman	30370	95510	14574
Nelson	2546	2342	637
Marlborough	145033	275651	29449
Total	**2910997**	**10068667**	**1237550**

For each region, the relative distribution of hill land between the different soil drainage, aspect and slope classes were estimated as described in section 4.2 (Table 4). These results show that about 85% of New Zealand hill land soils are well drained, but that some variability exists between regions. For example, in Northland and Auckland the majority of soils are classified as imperfectly draining, while Wellington, Hawkes Bay and Southland have ‘above-average’ distributions of imperfectly draining soils. Northland is the only region with a relatively large area of soil classified as poorly draining (14%, compared to 0 to 4 % for all of the other regions). Not surprisingly, the relative distribution of NW vs SE aspects is very similar for all regions and on average 34% and 66% respectively. The relative distribution of slope classes is also relatively constant, although Taranaki and Canterbury have a slightly larger percentage of high slopes. It should be noted, however, that due to the approach taken in this study to define hill land (using the 25-m resolution slope layer in the Digital Elevation Model), it became apparent that the areas under the low slope classes within the hill land might have been underestimated, and the relative distribution of hill land between the different slope classes needs to be treated with caution.

Table 4 Relative distribution of total area of hill land within each region and for total NZ hill country between the different soil drainage, aspect or slope classes
(

Class / Region	Free draining	Imperfectly draining	Poorly draining	NW aspect	SE aspect	Low slope	Medium slope	High slope
Northland	33	53	14	34	66	17	77	6
Auckland	41	55	4	35	65	16	78	7
Waikato	87	11	3	34	66	12	78	10
Bay of Plenty	99	0	1	34	66	12	75	13
Gisborne	92	7	1	34	66	8	74	18
Hawke's Bay	85	15	0	34	66	10	75	15
Taranaki	99	0	1	33	67	6	64	30
Manawatu-Wanganui	89	10	1	34	66	7	72	21
Wellington	78	21	1	33	67	8	77	15
West Coast	94	3	3	36	64	14	73	14
Canterbury	88	12	0	34	66	6	63	30
Otago	91	9	0	34	66	8	70	21
Southland	69	30	0	34	66	10	72	17
Tasman	91	7	2	34	66	9	70	22
Nelson	99	1	0	35	65	6	72	22
Marlborough	92	8	0	35	65	4	55	41
Total area	**85**	**13**	**1**	**34**	**66**	**8**	**71**	**21**

5.2 Nitrogen excretion rates

The amount of N excreted in each region was calculated based on the number of sheep and beef cattle per region occupying hill country using the method of Clark et al (2003) as used in the New Zealand inventory (Table 3). The total amount of N excreted by these animals was then calculated for each HLU by first apportioning the excretal N across soil drainage class based on the relative distribution of these classes, and then by partitioning and apportioning excretal N across slope and aspect categories as described in the nutrient transfer model of (Saggar *et al*. (1990a, b) (Appendix 1; Table 5).

As a result of the uncertainties on the estimates of the total area of low slopes/camp sites, the total number of animals and thus the total amount of N excreted in hill land might have been over- or under-estimated. However, as N excretion within each HLU was estimated irrespective of the area of land within each HLU but based on the nutrient transfer model, the relative distribution of N excreted within each slope class is not affected by any underestimation of the area of land in low slopes.

The results show that low slope/camp areas (HLUs 1, 4, 7, 10, 13, 16) receive 57% of total excretal N as a result of animal grazing and camping behaviour (see also Table 8), with the majority of excreted on low slope classes on free draining soils (45%). Medium slope areas on well drained soils (HLUs 2 and 5) receive 24% of the total excretal N, while the remaining excretal-N is deposited on steep slope areas of freely drained soils (10%) and on medium and steep slope areas of imperfectly and poorly drained soils (9%).

Table 5 Total amount of N excreted in each HLU by region and nationally (kg excretal N) and the percentage of N excreted in each HLU nationally (%)

HLU code[a] / Region	FNL 1	FNM 2	FNH 3	FSL 4	FSM 5	FSH 6	INL 7	INM 8	INH 9
Northland	1345081	722096	292614	2619084	1406034	569766	2160055	1159608	469907
Auckland	972768	522223	211620	1789418	960635	389277	1252230	672250	272415
Waikato	3183310	1708935	692510	6131393	3291590	1333847	387107	207816	84213
Bay of Plenty	1065700	572113	231836	2108568	1131968	458706	5152	2766	1121
Gisborne	1151742	618304	250554	2274208	1220891	494740	94664	50819	20594
Hawkes Bay	2407343	1292363	523703	4640493	2491212	1009511	424523	227902	92352
Taranaki	958914	514786	208606	1915095	1028104	416617	51	27	11
Manawatu-Wanganui	5022767	2696433	1092672	9627564	5168481	2094417	584814	313953	127223
Wellington	1832629	983832	398677	3691136	1981557	802984	474776	254880	103285
West Coast	109079	58558	23729	201127	107974	43754	4076	2188	887
Canterbury	5513476	2959866	1199423	10911998	5858020	2373838	749404	402312	163028
Otago	8677099	4658232	1887650	16947428	9098093	3686809	870003	467054	189264
Southland	3848286	2065922	837171	7378932	3961321	1605241	1661157	891779	361374
Tasman	452406	242871	98418	860748	462086	187250	35607	19115	7746
Nelson	16463	8838	3581	30384	16311	6610	331	177	72
Marlborough	1184113	635682	257597	2154723	1156746	468747	103991	55826	22622
Total N excreted (kg N)	37741176	20261052	8210361	73282298	39341023	15942114	8807939	4728473	1916113
% of total N excreted in each HLU	15.4%	8.3%	3.4%	29.9%	16.1%	6.5%	3.6%	1.9%	0.8%

HLU code[a] / Region	ISL 10	ISM 11	ISH 12	PNL 13	PNM 14	PNH 15	PSL 16	PSM 17	PSH 18
Northland	4208332	2259210	915497	586291	314746	127544	1160956	623250	25255
Auckland	2394697	1285574	520952	89304	47942	19428	171141	91876	3723
Waikato	743387	399081	161719	104722	56219	22782	201931	108405	4392
Bay of Plenty	9135	4904	1987	6604	3545	1437	14876	7986	323
Gisborne	179344	96279	39015	6799	3650	1479	13278	7128	288
Hawkes Bay	827966	444487	180119	12011	6448	2613	24817	13323	539
Taranaki	133	71	29	14089	7564	3065	25170	13513	547
Manawatu-Wanganui	1104418	592898	240259	62885	33759	13680	106941	57410	2326
Wellington	970691	521108	211168	25231	13545	5489	49705	26683	1081
West Coast	5311	2851	1155	4395	2359	956	6517	3499	141
Canterbury	1429915	767639	311069	8195	4399	1783	15746	8453	342
Otago	1598072	857912	347651	26310	14124	5724	50451	27084	1097
Southland	3220367	1728829	700571	26922	14453	5857	53149	28533	1156
Tasman	65451	35137	14239	9672	5193	2104	22297	11970	485
Nelson	224	120	49	5	2	1	10	6	
Marlborough	191576	102846	41676	128	69	28	85	45	1
Total N excreted (kg N)	16949017	9098946	3687155	983563	528018	213968	1917069	1029163	41704
% of total N excreted in each HLU	6.9%	3.7%	1.5%	0.4%	0.2%	0.1%	0.8%	0.4%	0.2%

[a] Code xyz = drainage, aspect, slope; Drainage = F, I, P (free, imperfectly, poorly); Aspect = N, S (NW and SE); Slope = L, M, H (low, medium, high)

5.3 Relative contribution of each HLU to total N2O emissions from hill country

In all scenarios tested the greatest (> 50 %) contribution of N_2O emissions from hill land occurred in areas that are low slope/camp areas on free draining soils (Table 7). Whilst the proportional contributions of the low slope areas vary somewhat between the different scenarios, these areas stood out as the dominant source of N_2O emissions in hill land. Use of a constant EF_3 of 1% as in the New Zealand inventory suggests that HLUs classified as low slope/camp areas contribute 57% of total N_2O emissions in hill country (Table 8). However, other scenarios which take into account the differences in emissions at different slope and aspect categories show that HLUs in low slope/camp areas can contribute between 82 – 95% total hill land emissions. This reflects the fact that low slope/camp areas, although occupying a relatively small area of the land, receive 57% of all N excreted in hill land (Table 8), indicating that 'slope' can have a major influence on N_2O emissions. In contrast, for 'drainage class' and 'aspect', the relative contributions of land area and total N excreted are very similar, indicating that N excretion rate is not affected by these categories. As a result, the relative contribution of drainage class and aspect to total N_2O emissions is driven by land area, rather than N excretion rate.

Due to the high proportion (85%) of free draining soils, these soils contribute the most in N_2O emissions in hill land. Even under scenario VI which has a very high EF_3 for poorly draining soils, free draining soils still contribute two-thirds of total emissions.

The effect of aspect is less pronounced and the relative contribution of either NW or SE generally ranges between 40-60%. The exception is scenario VI when NW aspects contribute 80% of the total N_2O emissions from 34% of the land area (Table 8). In the current study, we assumed that NW aspects have higher emission factors due to animal preference for these warmer/sunnier aspects resulting in more compaction and higher fertility. This assumption needs further testing and validation as these NW HLUs are likely to have lower soil moisture contents than the SE aspects, which could result in lower EF_3.

Table 7 Percent contribution of each HLU to total hill land N_2O emissions under a range of emissions scenarios (for values EF_3 for each of the 6 scenarios refer to Table 2, page 6)

HLU code[a]	FNL 1	FNM 2	FNH 3	FSL 4	FSM 5	FSH 6	INL 7	INM 8	INH 9	ISL 10	ISM 11	ISH 12	PNL 13	PNM 14	PNH 15	PSL 16	PSM 17	PSH 18
Scenario I[1]	15.4	8.3	3.4	29.9	16.1	6.5	3.6	1.9	0.8	6.9	3.7	1.5	0.4	0.2	0.1	0.8	0.4	0.2
Scenario II[2]	36.7	6.6	0.3	23.8	1.3	0.5	8.6	3.1	0.1	11.0	3.0	0.1	1.3	0.5	0.1	2.5	0.7	0.1
Scenario III[3]	37.9	6.1	0.4	22.1	2.0	0.8	8.9	2.9	0.1	10.2	2.7	0.2	1.5	0.5	0.1	2.9	0.6	0.1
Scenario IV[4]	35.9	6.4	0.5	23.2	2.5	1.0	8.4	3.0	0.1	10.7	2.9	0.2	1.2	0.5	0.1	2.4	0.7	0.1
Scenario V[5]	44.2	4.7	0.4	17.2	1.8	0.7	10.3	2.2	0.1	7.9	2.1	0.2	2.3	0.6	0.1	4.5	0.5	0.1
Scenario VI[6]	58.9	1.6	0.0	5.7	0.1	0.0	13.7	1.5	0.0	5.3	0.7	0.0	3.8	0.8	0.0	7.5	0.3	0.0

[a] Code xyz = drainage, aspect, slope; Drainage = F, I, P (free, imperfectly, poorly); Aspect = N, S (NW and SE); Slope = L, M, H (low, medium, high)
[1]Scenario 1 = EF_3 constant at 1 % for all HLUs as in NZ Inventory
[2]Scenario II = a relatively high EF_3 for all HLUs
[3]Scenario III = a moderate/reasonable EF_3 for all HLUs
[4]Scenario IV = a slightly less than moderate/reasonable EF_3 for all HLUs
[5]Scenario V = fairly low EF_3 for all HLUs
[6]Scenario VI = a very high EF_3 for HLUs that are expected to have high emissions, and a very low EF_3 for HLUs that are expected to have low emissions

Table 8 Relative contributions of land area, N excreted and N_2O emissions per drainage class, aspect and slope category.

	Area (%)	N excreted (%)	Relative contribution in N_2O emissions (%) Scenario I	II	III	IV	V	VI	Range
Drainage									
Free	85	79	79	69	69	70	69	66	66-79
Imperfectly	13	18	18	26	25	25	23	21	18-26
Poorly	1	2	2	5	6	5	8	13	2-13
	100	100	100	100	100	100	100	100	
Aspect									
NW	34	34	34	57	58	56	65	80	34-80
SE	66	66	66	43	42	44	35	20	20-66
	100	100	100	100	100	100	100	100	
Slope *									
Low	8	57	57	84	83	82	86	95	57-95
Medium	71	31	31	15	15	16	12	5	5-31
High	21	12	12	1	2	2	2	0	0-12
	100	100	100	100	100	100	100	100	

* Note: due to the approach taken in this study to define hill land (using the 25-m resolution slope layer in the Digital Elevation Model), the areas under the low slope classes within the hill land might have been underestimated. Therefore, the relative distribution of hill land between the different slope classes needs to be treated with some caution. However, the relative differences in the amount of N excreted and of the estimates N_2O emissions between slope classes are still valid.

Total N_2O emissions calculated for each of the different scenarios are given in Figure 3, which clearly shows how the total emissions from hill land may vary with the use of different EF_3 values for HLUs with different slopes, drainage classes and aspects compared to using a constant EF_3 for all hill land. However, more work is required to verify the assumptions that underpin the different scenarios. Given the prevalence of free draining soils, the current assumption that EF_3 of these soils is generally low or very low should be tested. In addition, the total emissions of N_2O from hill land were also sensitive to the relativities and absolute values used to assign an EF_3 to the different HLUs.

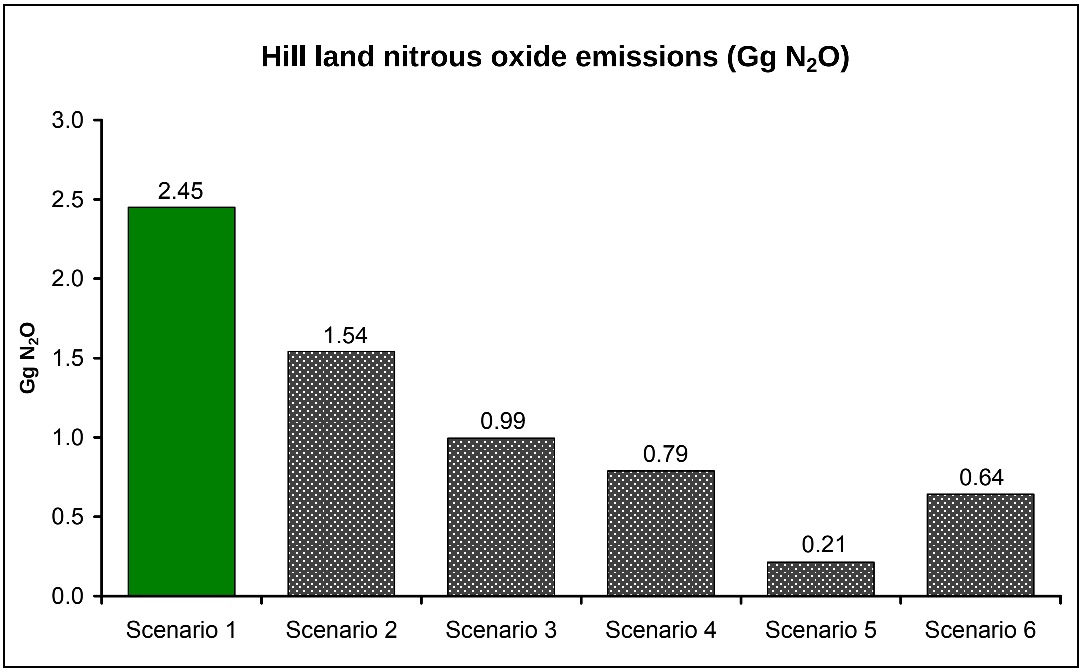


Figure 3 Total N_2O emissions from hill land areas for each of six scenarios

Scenario 1 = EF_3 constant at 1 % for all HLUs as in NZ Inventory; Scenario II = a relatively high EF_3 for all HLUs; Scenario III = a moderate/reasonable EF_3 for all HLUs; Scenario IV = a slightly less than moderate/reasonable EF_3 for all HLUs; Scenario V = fairly low EF_3 for all HLUs; Scenario VI = a very high EF_3 for areas that are expected to have high emissions and a very low EF_3 for areas that are expected to have low emissions

Please note: due to the uncertainties in estimating the area of hill land under low slopes/camp sites, the total amount of N_2O emissions estimated could be underestimated. However, the relative differences between the scenarios are still valid.

Of the scenarios other than the currently used approach (a constant EF_3 of 1% for all HLUs), the highest total emissions from hill land were obtained when a relatively high EF_3 was assigned to each category of HLU (Scenario II Figure 3; refer also to Table 2). Based on our current knowledge of drivers of N_2O emissions scenario II represents a relatively high EF_3 for all HLUs. Nevertheless, total emissions were still lower than when a constant EF_3 of 1% was used for all hill land. The scenarios tested here illustrate the potential for a reduction in New Zealand's GHG inventory when a range of EF_3 values are assigned to the different HLU's. However, more work is required to verify our assumptions.

6. Discussion and Conclusion

In hill country the driving variables for N_2O emissions and the topography-driven spatial variability of these drivers are well known. In this study, hill land was disaggregated into 18 HLUs based on soil drainage class, topography and aspect, and total N_2O emissions were estimated as a product of a) the total area of land in each HLU, b) the N excretion rate in each HLU, and c) the EF_3 assigned to that HLU:

$$N_2O_{Hill\ country} = \sum_i (HLU_i \bullet Nreturn_i \bullet EF_{3i})$$

Where,

HLU*i* = Area of land in Hill country Land Unit *i*, as defined by slope, aspect, and drainage class; *i* = 1, …n. (ha)

Nreturn *i* = amount of excreta N deposited in HLU *i* (kg N excreted/ha)

EF_3 *i* = N_2O emission factor for N deposited in HLU *i* (kg N_2O-N/kg N excreted)

Our study shows that this approach provides a very useful framework for upscaling the spatially variable N_2O emissions in hill country. The interaction of the three variables determines the relative importance of each HLU to the total N_2O emissions from hill land. Therefore, the accuracy of estimating the values of each of these three variables is critical for accurately estimating the N_2O emissions.

Area of each HLU

These were estimated by first defining the total area of hill land, which was then overlaid with data from additional spatial data layers including aspect, the LENZ drainage layer, and further analysis of the 25-m resolution slope layer. Although the approach was relatively straightforward, our definition of hill land (section 4.2) may have been restrictive. For example including hill land used for dairy grazing, not an uncommon practice in recent times, will have increased the total area somewhat. On the other hand, our criteria of including only land predominantly >12° will have excluded any hill land on slopes <12°. As a result of this approach, low slope areas/camp sites within hill land are likely to be under-represented and their total area underestimated. We also excluded areas in hill country under crop, some of which would be grazed (i.e. forage brassicas). The criteria we chose to identify hill land in this study may be further improved to account for other areas of grazed hill land. However, as the primary aim of this study was to provide a framework for estimating N_2O emissions from hill land and to identify key research priorities (rather than quantifying these emissions), the criteria we used were appropriate and reasonable.

Nitrogen excretion

Nitrogen excretion in each HLU was determined by i) the spatial location of animals and animal numbers and ii) the distribution of excreted N between different HLUs. We estimated the spatial distribution of the animals using total stock numbers obtained from the AgriBase Data Base and the spatial information of the AgriBase Data Base farms. In hill country livestock numbers and categories can change rapidly in response to key economic drivers. Accurate tracking of these changes and their subsequent effect on New Zealand's N_2O inventory is crucial. Due to the availability of a number of animal data bases it should theoretically not be difficult to obtain accurate estimates of these numbers. Likewise, the amount of N excreted per animal was calculated using the approach of Clark *et al*. (2003) and is in accordance with the New Zealand inventory. Our estimates of excreta N return to each HLU were based on the nutrient transfer model we used. At present it is the only model which exists for estimating nutrient transfer for New Zealand hill land, and further validation of the model is warranted.

Low slope areas on freely draining soils (HLUs 1, 4) had the greatest impact on total N_2O emissions, irrespective of their assigned EF_3 (contributing 45-65% of emissions). This was primarily due to the large proportion of total excreta N being deposited in these camping areas as a result of animal grazing and camping behaviour. Although low slope areas on freely draining soils occupy a relatively small area of hill land, our calculations suggest they receive 45% of excreta N. The amount of excreta deposited in a HLU is driven by its topography and aspect and animal behaviour responses to these. Due to camping behaviour the majority of excretal N is deposited on low slopes and this makes these sites surplus in N and therefore the key source of N_2O emissions. In our study, the relative contribution of emissions from HLUs situated at low slope camp sites was 5 to 20-fold higher than those from moderate and high slopes combined (Table 8).

Emission factors

The emission factors we used in the different scenarios were based on our current understanding of the drivers of N_2O emissions. However, there is very limited N_2O emissions data available for New Zealand hill country, and there is incomplete information on emissions from sheep and beef grazed hill country pastures to assign fully reliable EF_3 values for quantifying the total N_2O emissions from hill land. We have used a first principle approach for assigning EF_3 for HLUs throughout the study, and these are open to debate.

In hill country, grazing management, stocking density and fertiliser inputs are often not as intensive as they are in flat land areas. Most of the work done to refine the EF_3 for grazed land in New Zealand has been conducted on intensively grazed land of easy to flat contour. The small amount of work done to calculate EF_3 in hill country has focussed on easier contour and camp site areas in just two isolated areas of hill country. In these areas EF_3 has been found to be not dissimilar to that in flat land. Our analysis suggests that whilst just over half of nutrients excreted in hill country tend to be on easier contour and camp site areas, a substantial amount of excreta will fall on MS and HS areas. The EF_3 of excreta deposited in these areas is unknown. It is the uncertainty surrounding the EF_3 for the hill country that requires the greatest attention, not only for the refinement of N_2O emissions calculations but also for assessing the impact of strategies to mitigate these emissions. Due to the lack of N_2O emissions factor data available for hill country, it was not possible to perform a reasonable uncertainty analysis of the N_2O emissions estimated in this study.

Hill country comprises a large proportion of total grazed land in New Zealand, and significant numbers of livestock graze in New Zealand hill country. Given the IPCC method for calculating N_2O emissions, it would be prudent for New Zealand to investigate the refinement of EF_3 for areas of hill country.

7. Recommendations

In order to facilitate the refinement of estimates of N_2O emissions in New Zealand and to evaluate the contribution of hill land areas to national total N_2O emissions, we recommended that the following actions are given priority:

2. Refining N_2O emission factors

Our study highlights the need for various EF_3 research priorities to further improve New Zealand's N_2O inventory. These should be targeted at determining N_2O emission factors (EF_3) on those hill land areas which contribute most to N_2O emissions, or where the largest uncertainties exist:

a. Test framework in key regions with good spatial data
b. Refinement of EF_3 in low slope areas
c. Refinement of EF_3 in free draining soils
d. Determining the effect of aspect on EF_3

a. Test framework in key regions with good spatial data

As some of the uncertainty of the relative N_2O emissions from the different HLUs is due to uncertainty on the animal numbers and the areas of land within each HLU, it is recommended to test our framework in one or two representative districts/regions for which good spatial data is available. This will reduce some of the uncertainty around the animal numbers, the areas of land within each HLU and N excreta distribution, and will confirm the key HLUs that make the largest contribution to overall N_2O.

b. Refinement of the EF_3 in low slope areas

Low slope/camp areas are estimated to contribute between 57 and 95% of total N_2O emissions. From the results presented here the relative importance of the amount of N excreted vs. the EF_3 of low slope areas in determining total N_2O emissions are difficult to determine as these interact and both are important in determining total emissions. Where excretal N deposition rates are high, emission factors are also likely to be relatively high. A field campaign determining EF_3 in low slope areas under contrasting climatic conditions and receiving low, medium or high N inputs is required to refine the EF3 for HLUs that are estimated to make the largest contribution to total N_2O emissions.

c. Refinement of EF_3 in free draining soils

Due to the high prevalence of free draining soils, these soils contribute the majority of N_2O emissions in hill land. Additional field work to determine EF_3 is particularly required in free draining low and medium slope hill areas. First principles would indicate that EF_3 in these areas is expected to be low, and hence our calculations suggest that these areas, although receiving 24% of the excreta N inputs, generally contribute less then 8% of total N_2O emissions. However the assumption that EF_3 in these areas is low needs to be tested. If proved otherwise, freely draining medium slope hill areas could make a larger contribution to total N_2O emissions than we have estimated in this study.

d. Better understanding of the effect of aspect on EF_3

The relative contribution of either NW or SE generally ranges between 40-60%. However, under scenario VI that assumes a high emission factor for HLUs in the very high and high emission factor categories, NW aspects contribute 80% of the total N_2O emissions, while land area contributes only 34%. This probably reflects the current assumption that NW aspects have higher emission factors due to animal preference for these warmer/sunnier aspects resulting in more compaction and higher fertility. On the other hand, these aspects are likely to have lower soil moisture contents than the SE aspects, which could result in lower emission factors. Again, the assumption that EF_3 on NW aspect are high needs to be tested to ensure our current estimates are not overestimating N_2O emissions of these areas.

3. Obtaining accurate and up to date estimates of animal numbers

Obtaining up to date figures on animal numbers was a real challenge. There are discrepancies in animal numbers between spatial and non-spatial data sets with no way of validating either given the resources and time allocated to this project. Nevertheless this remains an area of great importance, as animal numbers are a major driver of N_2O emissions calculations regardless of whether a spatial disaggregation is used. An investigation on updating the current animal number data sets is therefore recommended.

4. Estimating N excretion in each HLU

Our estimates of excreta N return to each HLU was heavily dependant on the nutrient transfer model used. There is a need to assess this model's applicability over a greater range of hill land compared to the hill areas in which it was validated. At present it is the only model which exists for estimating nutrient transfer for New Zealand hill land, and we have no reason to doubt its validity other than that stated. Nevertheless, as the relative distribution of N deposited in the different slope classes was a key determinant of N_2O emission, further validation of the nutrient transfer model with the excretal N deposition data on these HLUs is required.

Our conclusions and recommendations are limited to a degree by the constraints discussed above. However, the absolute area of hill land, and the absolute number of animals grazing hill land areas were not of greatest importance for this study, as the objective was not to accurately estimate total N_2O emissions from hill country. Rather, the objective was to provide:

- A framework for estimating and up-scaling N_2O emissions from hill country farms, based on current understanding of the key factors affecting the spatial variability in N_2O emissions and utilising existing spatial databases of land, soil and animal classes/density in NZ hill country.
- Recommendations for the most effective field campaigns to be conducted to determine EF_3 in key Hill country Land Units (HLU) in NZ.

We feel that the results presented here within the timeframe and funding constraints of the project have addressed the objectives well. Our word of caution would be that any field work to address the issues raised in this desk top study be done in close conjunction with systems-based modelling. There is much scope for this work to be extended and we look forward to debate and feedback on the issues raised.

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9. Appendices

9.1 Appendix 1: Description of the Nutrient Transfer Model used to estimate N excretion rates in the Hill Land Units

A complete outline of the NTM is presented in Saggar *et al*. (1990a, b). The model is flexible to take into account the unique rates of N deposition, response to added N, and production potentials by partitioning the farm area into different HLUs and thereby integrates the effects of category-specific measurements to explain the overall fate of N within the farm. A recent study (Carran and Saggar 2004) tested this above-ground NTM, using data from long-term hill-country farms, to calculate N transfers in different slope classes and aspect categories through animal excreta. The equations given in Table 1 were used to estimate N transfers through animal excreta for three farmlets set-stocked with sheep and representing low (LF), medium (MF) and high fertility (HF) status, at the Ballantrae AgResearch Hill Country Research Station (Carran & Saggar 2005). Annual pasture production at the LF, MF and HF farms during 1993–94 was 4918, 10149 and 14120 kg/ha, respectively (Saggar et al. 1997). The herbage N concentration increased with increasing fertility and averaged 2.06, 3.05 and 3.40% in the LF, MF and HF farms, respectively. The LF, MF and HF farms were stocked at approximately 6.3, 12.9 and 22.0 SU/ha (SU = Stock Unit).

Annual pasture production in each HLU, pasture N concentration and measured pasture utilisation provided animal uptake of N from each HLU. Since site specific values for pasture production were not practical to obtain, it was assumed that pasture production would be directly proportional to the stocking densities in these areas.

The distribution of farmlet areas in each slope-aspect category is given in Table 2. The 'sunny' areas facing north-west (NW) were warmer and drier compared with cooler, damper 'shady' areas facing south-west (SW). The east (E) aspect was intermediate in these characteristics. Wind direction prevailing from NW further influenced the stock behaviour and therefore excretal returns.

Table 1 Summary of nutrient–transfer model (NTM) equations to estimate N input from grazing animals in each hill-land unit (HLU) in hill-country grazed pastures

Parameters and symbols

Slopes: L, M, S = Low (1-12°), medium (13-25°) and steep (>25°) slopes, respectively

Aspects: SW, NW = South West and North West

SW_a, NW_a = Percent of total measured area in each aspect category

L_a, M_a, S_a = Percent of total measured area in each slope category

DM_{fS1} = the contribution of pasture production each slope (kg DM) weighted by stratum area

HA_{LSW}, … = measured herbage accumulation in each slope (kg DM); LSW represents L slope and SW aspect; ….signifies similar symbols or calculations for other slope × aspect strata

a_1 = percentage of total measured farm area in respective slope × aspect

PNC_{S1} = Pasture N concentration (%) in respective slope × aspect

$ANUP_{S1}$,… = N intake by animal from each slope × aspect

SUM (ANUP) = Total N intake (kg/ha)

D_{S1},…. = Percentage of dung deposited in each slope × aspect

U_{S1},…. = Percenage of urine deposited in each slope × aspect

K_D, K_U = Proportion of N in dung and urine, respectively

$EXCRT_{S1}$,.. = Percentage of total N return on each slope × aspect

$DEPOT_{S1}$,.. = Amount of N deposited (kg/ha) in each slope × aspect

Animal uptake of Nitrogen

$HA_{fS1} = HA_{SI} \times a_{1/100}$ for S1, S2, ……SN

$ANUP_{S1} = HA_{fS1} \times HNC_{s1}$ for S1, S2, ……SN

$SUM (ANUP) = ANUP_{S1} + \ldots + ANUP_{SN}$

Excretal Returns

$EXCRT_{S1},\ldots = (D_{S1} \times K_D) + (U_{S1} \times K_U)$

Nitrogen Input

$DEPOT_{S1},\ldots = 0.85 \times SUM (ANUP) \times EXCRT_{S1/100}$ for S1, S2, ……SN

Table 2 Percent distribution of farmlet area in each slope-aspect category

Farmlet	Slope category			Aspect category		
	Low (1-12°)	Medium (13-25°)	Steep (>25°)	NW (275-35°)	E (35-155°)	SW (155-275°)
LF	33	42	25	56	20	24
MF	37	37	26	54	36	10
HF	23	44	33	40	53	7
Mean	31	41	28	50	36	14

Of the total excretal returns at Ballantrae farmlets approximately 60 (D_L), 30 (D_M) and 10% (D_S) dung, and 55 (U_L), 31 (U_M) and 14% (U_S) of urine were deposited by sheep at Low (1-12°), Medium (12-25°) and Steep (>25°) slopes, respectively (Saggar et al. 1988). A 60 to 40 ratio of excretal-N in urine to dung was used in the model. In this model, the amount of N removed in animal products accounted for 15% of the N taken up by the animals [SUM (ANUP)]. The remaining 85% of the N consumed by the sheep was returned (DEPOT) in the excreta with various proportions of the total excreta ($EXCRT_{S1}$/100) being returned to each HLU.

The final N input in each HLU calculated by accounting for proportional area of each slope-aspect stratum (Table 3), shows the variations in N deposition through animal excreta across HLUs in a sheep-grazed pasture. These results suggest that the NTM can be a useful tool for the estimation of N inputs across different HLUs of sheep, beef and sheep/beef grazed hill country pastures.

Table 3 Amount of N deposited (Kg N/ha) through animal excreta at each slope-aspect stratum

Whole farm N deposition (kg/ha)	E			SW			NW		
	Low	Medium	Steep	Low	Medium	Steep	Low	Medium	Steep
LF =60	271.2	128.6	76.0	36.6	13.9	11.7	72.5	26.4	16.4
MF =184	366.4	258.3	123.9	264.9	143.2	65.4	218.2	108.6	52.7
HF =285	619.4	228.6	102.9	937.9	269.5	112.6	733.7	190.9	86.4

9.2 Appendix 2: Literature review on the key factors affecting the spatial variability of N_2O emissions in hill country

Introduction

Direct and indirect nitrous oxide (N_2O) emissions from animal excreta deposited during grazing contribute over 80% of the total agricultural N_2O emissions in New Zealand. The current Intergovernmental Panel on Climate Change (IPCC) inventory methodology for calculating N_2O emissions from grazed land uses estimates of animal numbers, a set value for the amount of nitrogen (N) excreted per animal based on its estimated intake, and a constant value for the amount of N_2O emitted per unit of N excreted, termed the emission factor (EF_3) (EF_3 = 1%; see also Table 1). Whilst the methods for calculating animal numbers and the amount of N they excrete have been standardized based on New Zealand data (de Klein and Ledgard, 2005) the value used for EF_3 is surrounded by much more uncertainty. During the past decade a considerable amount of resource has been put in to measuring N_2O emissions from urine patches on grazed land in order to refine the emission factor for New Zealand. The majority this work has occurred on easily accessible and intensively managed flat land sites over a limited range of soil types in close proximity to research institutes. However, grazed hill country comprises 60% of the total farmed area of land in New Zealand with 25% of the national sheep flock and 20% of the beef cattle herd occupying hill country in the North Island. Currently, N_2O emissions from hill country are estimated in the same way as those from grazed flat land (i.e. multiplying the estimated amount of N excreted, based on animal numbers, with the same emission factor used for flat grazed land) but there is very little data to support or refute the use of an identical EF_3 for hill country and for flat land. Moreover, due to i) differences in the size and frequency of urination pattern between sheep and dairy cattle; ii) increased spatial variability in excreta N return in hill country; and/or iii) more pronounced spatial variability in soil parameters known to drive N_2O emissions (e.g. soil moisture and temperature) due to spatial differences in topography and aspect that are typical for NZ hill country, the emission factor from sheep or cattle urine patches in hill country are likely to be lower than that for flat land. Given the large number of animals occupying areas of hill country, there is therefore some uncertainty surrounding the current inventory estimates of N_2O emissions for New Zealand.

Until recently, there has been only one study of N_2O emissions in what could be classified as typical New Zealand hill country (Carran *et al*. 1995). The results of this study suggested that emissions of N_2O in hill country may be very low, even in stock camp areas, and that the EF_3 from animal excreta in hill country (albeit measured indirectly) may be lower than the 1% as set in the inventory methodology (Table 2). This was attributed to the increased spatial variability in excreta N return, as well as to the topography driven soil parameters and temperature conditions that regulate N_2O emissions. However, more recent work has demonstrated that the emission factor for synthetic sheep urine on low slopes in both easy rolling hill country and in more typical hill country could be as high as that from intensively farmed flat land sites (Tables 2 and 3) (Hoogendoorn *et al*. 2008), depending on level of grazing intensity and on fertiliser N input. In this trial N_2O emissions from non urine-amended sites for intensively grazed and nitrogen fertilised areas in hill country were comparable to that from flat land sites, especially when soil moisture levels were high. The key drivers of N_2O emissions are well known, and there is no reason to believe that these drivers would be any different over the range of soil types and conditions found on farmed land in New Zealand, including that in hill country. For a particular set of drivers, there is nothing unique about hill country *per se* that would indicate that emission factors for excreta deposited there should be any lower or higher than that at flat land sites with an identical set of drivers.

A brief review of N_2O emission processes

Several different microbial processes result in the production of N_2O in soils. The most significant of these processes are thought to be nitrification, nitrifier denitrification and denitrification. Autotrophic nitrifying bacteria are responsible for both nitrification and nitrifier denitrification in soils. In ammonia oxidation, the first stage of nitrification, ammonia is oxidised to nitrite (NO_2^-), and N_2O can develop as a by-product. As oxygen is required for this process, it takes place in aerobic micro-sites of soils. Nitrifier denitrification is a pathway that ammonia oxidisers are thought to turn to under short-term oxygen limitation whereby nitrite NO_2^- is reduced to molecular nitrogen (N_2) via N_2O. This reduction is thought to be similar to denitrification, whereby heterotrophic denitrifiers use nitrate (NO_3^-) or NO_2^- as an electron acceptor under low oxygen conditions. Although conditions which promote nitrification, nitrifier denitrification and denitrification differ, these processes are thought to take place simultaneously in different microhabitats of the same soil.

A brief review of processes affecting N_2O emissions from agricultural soils

Factors affecting the emission of N_2O from agricultural soils and grazed pastures have been well reviewed (e.g. Bolan *et al*., 2004; de Klein *et al.* 2001; Tiedje, 1988). Tiedje (1988) was the first to group environmental factors that affect denitrification into proximal and distal regulators. Proximal regulators affect the immediate environment of the microbial cell and include factors such as soil – N substrate concentrations, carbon (C) levels, oxygen content and temperature. Distal regulators control the proximal regulators on a larger scale and include factors such as plant growth stage, animal treading, defoliation and excretal return, soil texture, rainfall and irrigation. Specifically, N_2O emissions from grazed soils are positively correlated to soil NO_3^- and C concentrations, soil temperature, soil pH, and soil moisture levels. Soil moisture levels in turn determine the degree of anaerobicity or restricted oxygen availability in the soil.

Unique factors which characterise New Zealand hill country

Elevation, slope and aspect are the fundamental components that define hill country and hill country often has complex combinations of slope and aspect even within a small area. This heterogeneity increases the diversity of micro-climate (e.g. temperature, soil characteristics -in particular soil moisture), plant species composition, and the behaviour of grazing animals, which then further increases the complexity of pasture productivity patterns. Both the topographical features of hill country and the consequent uneven redistribution of nutrients in the landscape by animals grazing hill country affect the proximal and distal regulators of N_2O emissions.

Topographical features which affect the proximal and distal regulators of N_2O emissions

Relatively few areas of hill country have been studied in detail, and the examples cited below apply mainly to a small area of hill country in the southern Hawkes Bay. Nevertheless, there is no reason to believe that the relativities stated here would not be applicable over a wide range of hill country as noted by Saggar *et al*. (1990a, b) and Zhang *et al*. (2006). Most of the detailed soil and plant data available for hill country are based on one long term phosphorous fertiliser (P) trial and are summarised by Lambert *et al.* (2000) and Lopez *et al.* (2003), with supporting data from the studies of Sakadevan (1991) and Bowatte (2003). These authors examined the effects of long-term P fertiliser use, livestock management, slope category and aspect on the physical and chemical features of hill country soil and on herbage accumulation.

Slope

Greater differences in soil features were measured between slope categories than between different management treatments. Low slope (0-12°) (LS) areas had greater volumetric soil moisture content (VWC) than medium slope (13-25°) (MS) areas, which in turn had higher VWC than high slope (>25) (HS) areas. Total porosity decreased with increasing slope and soil bulk density increased with increasing slope. Increasing bulk density with increasing slope was felt to be most likely a consequence of decreasing organic matter concentration rather than the small differences in measured soil texture between the slope classes (Lambert *et al*. 2000). Air permeability was greater in HS than MS and LS soils and soil from LS areas was easier to compress than soils from MS and HS areas. Likewise soil rebound, expressed as a function of compression, was greater in MS and HS soils than LS soils.

On hill areas that had been hard grazed in winter by both sheep and cattle separately, Betteridge *et al.* (1999) reported higher soil bulk densities on tracks vs. MS and HS area for both animal types. This was attributed to the greater degree of soil compaction on tracks than slopes. Animal treading is an important cause of soil compaction (Tollner *et al*. 1990), and in an all-grass wintering system, cattle are often hard-grazed on pasture throughout winter and early spring. In this system, especially when the soil is wet, treading can cause a large amount of soil compaction, and this would be especially marked in high traffic areas such as tracks and camp sites.

In the studies of Lambert *et al*. (2000), Sakadevan (1991) and Bowatte (2003) soil total-N, organic C, Olsen-P, sulphate-sulphur and $NO3^-$-N were all higher in LS than MS and HS soils and soil ammonium-N $NH4^+$-N was higher in LS and MS than in HS soils.

Aspect

Soils on southwest and northwest aspects have been found to have a higher bulk density than soils on easterly aspects (Lambert *et al* 2000). Whilst easterly aspects had higher pasture production and soil fertility than southwest and northwest aspects in an earlier survey of that same area, differences in soil fertility and pasture production between these aspects were not as apparent 10 years later. This suggests the relationship between aspect and soil parameters and herbage production parameters may interact with pasture development stage at the micro level, as the area in question had undergone intensive management changes over the 10 years. However it is not known whether similar trends have been observed at a wider scale. There was no significant difference between aspects in the concentrations of total-N, sulphate-S and organic C, however total P, organic and inorganic P and organic-S were all higher on the eastern aspects compared to the northwest aspects, with southwest aspects having intermediary concentrations.

Nutrient transfer and its effects on the proximal and distal regulators of N_2O emissions

Grazing animals ingest nutrients from a wide area of a paddock and through the digestion, absorption and excretion process concentrate unutilised nutrients, particularly N, P, potassium, sulphur and C, in urine and dung patches. Organic forms of N excreted in the urine undergo rapid transformation to inorganic forms of N, namely ammonium ($NH4^+$) and $NO3^-$, once in contact with the soil. On intensively managed flat, land animals tend to graze in a spatially homogenous pattern as there is often little scope or cause for exercising preference for grazing and resting sites. Thus while nutrients are concentrated into urine and dung patch areas, the distribution of that excreta is relatively random at any grazing event, and so over time all areas in a paddock have an equal chance of receiving nutrients via excreta. In hill country, where grazing systems are often more extensive, animals have both a greater opportunity, and it could be argued a greater need, to show preference in choosing grazing, resting and therefore excreting sites. Animals tend to graze the easier slopes and warmer and more sheltered aspects before there is pressure for them to graze the steeper and/or more exposed country. And while animals will graze steeper and more exposed hill areas out of necessity, areas of ruminating, resting, and social interaction as well as excreting are generally confined to the easier slopes and sheltered aspects (Gillingham and During 1973; Saggar *et al*. 1990a, b; Rowarth *et al*. 1992; Betteridge *et al*. 2008). Over time, there is therefore a depletion of nutrients on steeper slopes and on shadier aspects and on aspects that are exposed to prevailing wind and rain. Conversely, there is a concentration of nutrients in flatter, sunnier and more sheltered areas. The relationship between slope class and/or aspect and the harvesting and excreting of nutrients is not a simple one however. Although patterns of animal behaviour that determine where an animal eats and where it excretes are determined by interactions between slope, aspect, other topographic features and current weather there are additional farm management factors such as stocking rate, grazing regime and size and shape of a paddock which also influence animal behaviour.

Saggar et al. (1990a, b) measured excretal return on a range of slope classes and aspects and calculated that 60, 30 and 19 % of dung and 55, 31 and 14% of urine was deposited on LS, MS and HS respectively (see also Appendix 1). This was reflected in the study by Lambert et al (2000) and Lopez et al (2006) who reported that soil total-N, organic C, Olsen-P, sulphate-S and $NO3^-$-N were all higher in LS than MS and HS soils and soil $NH4^+$-N was higher in LS and MS than in HS soils.

Using urination detectors and GPS units on sheep, Betteridge *et al*. (2008) found that there was a strong correlation between the time that sheep spent in an area and the number of urination events in that area (r = 0.88). They were able to present unique data showing that the longer an animal stays in, or the more frequently it visits an area, the greater the chance of urine being excreted there. In addition, the urination data confirmed that stock camps received a disproportionate amount of urine compared to the rest of the paddock. Similar results were found when Betteridge *et al*. used urination detectors and GPS collars on adult beef cattle grazing in hill country (unpublished data). Stock camps are found to contain more soil organic C, organic and inorganic P and S, and a higher pH, water soluble organic C, microbial biomass, and basal respiration than nearby grazing areas (Haynes and Williams 1999). Haynes and Williams (1999) concluded that the transfer of nutrients and organic matter from the main grazing areas to stock camps by grazing animals not only resulted in a decrease in nutrient status of the main grazing area, but also in a decline in soil biological activity relative to that in the camp area.

There have been a number of attempts to describe and/or model nutrient transfer in hill country both directly or indirectly in order to understand and predict the spatial variability and status of various soil nutrients and/or pasture production in the landscape. Saggar et al (1990a, b) modelled the transfer of nutrients in hill country in order to describe the spatial distribution of the P and S in hill country, and Bowatte *et al*. (2007) modelled N cycling and losses over broad categories of hill country. Zhang *et al*. (2006) provided a decision tree approach to modelling herbage production within a hill landscape, which could be used as an indirect method for categorising areas of likely high, medium and low N and soluble C in the soil.

Unique factors influencing N_2O emissions in hill country

Whilst large spatial and temporal variability in N_2O emissions have been measured between sampling sites within a discrete area for intensively managed flat land sites, this is likely to be even more pronounced in hill country. The variables which drive N_2O production are more spatially variable in hill country than on intensively managed flat land. Elevation, slope and aspect will of themselves produce variation in temperature, soil, and soil water content which will alter the potential for N_2O emissions and the N_2O emission factor. In addition, the effect of the grazing animal, as the agent of nutrient transfer, is also likely to have an important effect on N_2O emissions, as this will determine the availability of substrate for nitrification, nitrifier denitrification and denitrification .The unique factors which characterise hill country and their likely influence on the N_2O emission factor and the transfer of excreta N can give some guidance in refining the estimation of emissions of N_2O from hill country. It is noteworthy that the effects of slope on the N_2O emission factor and on the N excretion rates are likely to be compounding. In other words, areas with high N excretion rates (e.g. campsites) also tend to exhibit conditions that increase the N_2O emission factor (higher soil moisture content). On the other hand, the effects of aspects could be opposite, with sunnier/warmer aspects having higher N excretion rates yet likely to have lower soil moisture content and thus lower emission factors.

Although Carran *et al.* (1995) measured very low emissions of N_2O from flat campsite areas in hill country; this may have been partially due to the complete reduction of NO_3^--N to N_2 in conditions of high soil moisture. This possibility may also explain some of the variability experienced in field measurements of N_2O emissions in both flat and hill land environments as it must be remembered that N_2O gas is merely an intermediary in the complete reduction of NO_3^--N to N_2 gas. More detailed field measurements of the denitrification process would be helpful for understanding, modelling and predicting N_2O emissions from both flat and hill grazed land. It is also important to note that Carran *et al.* (1995) used a soil core incubation technique to measure N_2O emissions, rather than the now standardized static chamber technique employed in more recent studies. It is therefore difficult to compare the work of Carran et al (1995) with that of more recent studies (Hoogendoorn *et al*. 2008).

The work of Hoogendoorn *et al* (2008) reinforces the importance of the simultaneous presence of more than one key driver (i.e. high N substrate and high soil moisture conditions) for high N_2O emissions to be expected. Nitrous oxide emissions were much higher in the wetter than in the drier spring for both the Ballantrae and Invermay sites (Table 3), even though N inputs were similar between the 2 years.

Emissions of N_2O measured over a 10 week period from early spring on a poorly drained silt loam soil in easy rolling hill country at Invermay in Otago were reported to be 9, 22, and 166 g N_2O-N/ha.day for paddocks that had received 0, 100, and 500 kg fertiliser N/ha.yr for 2 years (Selai Letica unpublished data). In this study the highest daily N_2O emission rates were in areas of the 500N paddocks which had the highest soil moisture levels.

The effect of slope *per se* on N_2O emissions have been explored in a recent small trial at Ballantrae. Emissions of N_2O measured on a poorly drained silt loam (Ballantrae, southern Hawkes Bay) in early winter of 2007 over a 5 day period were 4 times higher on flat (6 °) wetter areas vs. steeper (>20°) and drier areas of a hill paddock which had received 750 kg fertiliser N/ha.yr for 3 years (pers. comm. Leighton Parker, Massey University - data not yet published). An adjacent paddock which had received 100 kg fertiliser N/ha.yr for 3 years had much lower emissions (approximately 10% of that measured in the 750 N paddock) for both the flat and steep areas, although the flatter wetter area in this paddock had approximately twice the emissions than the drier steeper area. The results reported for this albeit short term study do support our hypothesis that N_2O emissions are different at different slope categories and are affected by N input and soil moisture levels. These results also concur with current understanding of the drivers of N_2O emissions on flat land and confirm our hypothesis that these same drivers operate in hill country.

Table 1 New Zealand flat land N_2O emissions measurements

Reference	Flat Land Area	Soil type	N source	N input (Kg N/ha)	Daily emission rates (g N/ha.day	N_2O emission (%)	measurement period
Clough et al. 1996	Waikato	Silt loam + water table	Synthetic urine	500		1.5	153 days
		-water table	Synthetic urine	500		3.0	153 days
		Peat + water table	Synthetic urine	500		<1	153 days
		- water table	Synthetic urine	500		<1	153 days
Clough et al. 1998	Waikato	Clay	Synthetic urine	1000		1.9	112 days
		Peat	Synthetic urine	1000		1.9	112 days
		Sandy loam	Synthetic urine	1000		0.8	112 days
		Silt loam	Synthetic urine	1000		1.0	112 days
Mueller 1995	Canterbury	Silt loam	Sheep urine	293		1.0	46 days
		Silt loam	Cow urine	374		0.9	46 days
Mueller 1995	Canterbury	Silt loam	Synthetic urine	500 (summer)		0.1	90 days
				500 (autumn)		0.4	90 days
				500(winter)		0.2	90 days
				500 (spring)		0.3	90 days
Ruz-Jerez et al. 1994	Manawatu	Silt loam (well drained)	Sheep grazed (ryegrass/white clover)	Not given	1.3	1.0-1.3	24 months
		Silt loam (well drained)	Sheep grazed (herbal ley)	Not given	1.3	1.0-1.3	24 months
		Silt loam (well drained)	Sheep grazed (ryegrass/white clover)	Plus 400 fert N	5.3	1.0-1.3	24 months
Carran et al. 1995	Manawatu	Silt loam (poorly drained)	Beef grazed	Not given		1	24 months

Table 1 cont'd New Zealand flat land N_2O emissions measurements

Reference	Flat Land Area	Soil type	N source	N input (Kg N/ha)	Daily emission rates (g N/ha.day	N_2O emission (%)	measurement period
de Klein et al. 2003	Waikato	Silt loam (well drained)	Cow urine	592		0.6	4 months
		Organic (surface drained)	Cow urine	592		0.3	4 months
	Canterbury	Silt loam (moderately drained)	Cow urine	592		3.7	4 months
	Canterbury	Stony silt loam (well drained)	Cow urine	592		0.5	4 months
Saggar et al. 2004	Manawatu	Sandy loan	Dairy cow grazing	396 (animal excreta plus 130 kg/ha fertiliser N	26.4	2.0	12 months
	Tokomaru	Silt loam	Dairy cow grazing	345 (animal excreta plus 190 kg/ha fertiliser N	32.0	2.5	12 months
Saggar et al. 2007	Manawatu	Silt loam (poorly drained)	Sheep grazed	285 (animal excreta plus 36.8 kg/ha fertiliser N)	7.4	1.0	20 months

Table 2 New Zealand hill country N_2O emissions measurements

Reference	Hill Country Area	Soil type	N source	N input (Kg N/ha)	Daily emission rates (g N/ha.day	N_2O emission (%)	Measurement period
Carran et al. 1995	Southern Hawkes Bay Slope 15-30°	Silt loam (well drained)	Sheep grazed	160	≤ 1.4	0.3	2 years
	Southern Hawkes Bay Slope 0-8°	Silt loam (well drained)	Sheep grazed	234	2.7	0.4?	2 years
de Klein et al. 2003	Otago Easy rolling hill	Silt loam (poorly drained)	Cow urine	592		2.6	5 months
			Synthetic urine	592		2.0	5 months
			Sheep urine	296		2.4	5 months
Hoogendoorn et al. 2008	Southern Hawkes Bay Slope ~ 6°	Silt loam (poorly drained)	Sheep grazed (no N fert)		1.6 - 4.1		31 - 41 days
			Sheep grazed (no N fert) Synthetic urine	360	9.8 – 12.6	0.10 – 0.14	31 - 41 days
			Sheep grazed (100 N fert)		5.6 – 9.7		31 - 41 days
			Sheep grazed (100 kg fert) Synthetic urine	360	7.6 – 90.6	0.03 – 1.06	31 - 41 days

Table 2 cont'd New Zealand hill country N_2O emissions measurements

Reference	Hill Country Area	Soil type	N source	N input (Kg N/ha)	Daily emission rates (g N/ha.day	N_2O emission (%)	Measurement period
Hoogendoorn et al. 2008	Otago Easy rolling hill	Silt loam (poorly drained)	Sheep grazed (no N fert)		3.0 - 6.4		42 - 56 days
			Sheep grazed (no N fert) Synthetic urine	360	7.0 - 18.6	0.10 - 0.21	42 – 56 days
			Sheep grazed (100 N fert)		4.1 - 19.8		42 - 56 days
			Sheep grazed (100 kg fert) Synthetic urine	360	8.2 - 22.9	0.06 – 0.9	42 – 56 days
Letica unpublished	Otago Easy rolling hill	Silt loam (poorly drained)	Sheep grazed		9		70 days
			Sheep grazed plus 100 kg fert N/ha.yr		22		70 days
			Sheep grazed plus 500 kg fert N/ha.yr		166		70 days

Table 3 Daily emissions of N_2O (g N_2O-N/ha.day) and emission factor (EF) (%) (N_20-N emitted as a % of N added in synthetic urine) - Ballantrae and Invermay 2005 and 2006 (Hoogendoorn et al. 2008).

Ballantrae		Dry Spring (2005)		Wet Spring (2006)	
Fert N rate (kg N/ha.yr)		g N_2O-N/ha.day	EF (%)	g N_2O-N/ha.day	EF (%)
0	no urine	4.1		1.6	
	urine	9.8	0.1	12.6	0.14
100	no urine	5.6		9.7	
	urine	7.6	0.03	90.6	1.06
300	no urine	6.8		38.1	
	urine	10.0	0.06	93.2	0.72
750	no urine	10.2		38.4	
	urine	25.4	0.26	133.5	0.94

Invermay		Dry Spring (2006)		Wet Spring (2005)	
Fert N rate (kg N/ha.yr)		g N_2O-N/ha.day	EF (%)	g N_2O-N/ha.day	EF (%)
0	no urine	3.0		6.4	
	urine	7.0	0.1	18.6	0.21
100	no urine	4.1		19.8	
	urine	8.2	0.09	22.9	0.06
300	no urine	15.5		68.8	
	urine	23.4	0.18	73.8	0.09
500	no urine	40.0		36.0	
	urine	40.5	0.01	75.2	0.69