

TECHNICAL REPORT

Environmental Models, Modules, and Datasets

Review and update of a Nutrient Transfer model used for estimating nitrous oxide emissions from complex grazed landscapes, and implications for nationwide accounting

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Abstract

In New Zealand, nitrous oxide emissions from grazed hill pastures are estimated using different emission factors for urine and dung deposited on different slope classes. Allocation of urine and dung to each slope class needs to consider the distribution of slope classes within a landscape and animal behavior. The Nutrient Transfer (NT) model has recently been incorporated into the New Zealand Agricultural GHG Inventory Model to account for the allocation of excretal nitrogen (N) to each slope class. In this study, the predictive ability of the transfer function within the NT model was explored using urine deposition datasets collected with urine sensor and GPS tracker technology. Data were collected from three paddocks that had areas in low (<12°), medium (12–24°), and high slopes (>24°). The NT model showed a good overall predictive ability for two of the three datasets. However, if the urine emission factors (% of urine N emitted as N₂O–N) were to be further disaggregated to assess emissions from all three slope classes or slope gradients, more precise data would be required to accurately represent the range of landscapes found on farms. We have identified the need for more geospatial data on urine deposition and animal location for farms that are topographically out of the range used to develop the model. These new datasets would provide livestock urine deposition on a more continuous basis across slopes (as opposed to broad ranges), a unique opportunity to improve the performance of the NT model.

1 | INTRODUCTION

In grazed grasslands, livestock harvest herbage from pastures across the landscape and aggregate the excreta waste

Abbreviations: AIM, Agricultural Greenhouse Gas Inventory Model; EF₃, emission factor (N₂O–N emitted as % of excreta N applied); GHG, greenhouse gas; HS, high slope; LS, low slope; MAE, mean absolute error; MS, medium slope; NT, Nutrient Transfer.

nitrogen (N) in urine and feces. Urine patches are the single largest source of gaseous N losses to air provided by ruminants grazing agricultural landscapes (de Klein et al., 2006; Di & Cameron, 2002). Urine depositions on grasslands can result in significant amounts of nitrous oxide (N₂O) emission, a long-lived, potent greenhouse gas (GHG) with a warming potential that is almost 300 times greater than carbon dioxide on a 100-yr time horizon basis (Forster et al., 2007).

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Assigning different emission factors to urine and feces from grazed pastures allows for an improved quantification of N₂O emissions and more targeted mitigations (Chadwick et al., 2018; Krol et al., 2016).

Complex hill-country grazing landscapes provide natural conditions for the development of a spatial framework model that disaggregates ruminant excreta deposition and N₂O emission factors (i.e., EF₃; % of urine N emitted as N₂O–N) tailored to different slope classes. For example, Marsden et al. (2018) reported that sheep EF₃ values are lower on Welsh upland and hill areas compared with intensively managed lowlands. In addition to major factors controlling N₂O emissions, such as hydrological processes regulating soil water-filled pore space and aeration intensity (Gu et al., 2011; Vilain et al., 2010), reduced excreta N transformations and nitrification rates contribute to lower N₂O emissions from soils with increased slope gradients (Marsden et al., 2018; Sagggar et al., 2015).

With almost half of New Zealand's national livestock herd grazing hill country pastures (with slopes >15°) and with a vast proportion of New Zealand landscapes on medium slopes (MS; 12–24°) and high slopes (HS; >24°), it is essential to account for the effect of topography on livestock behavior and excreta return. This was achieved through the development and implementation of the Nutrient Transfer (NT) model (Sagggar et al., 2015). The NT model was developed to determine the effect of slope on livestock urine and feces deposition used to calculate N₂O emissions. The model is currently being used in the Agricultural GHG Inventory Model (AIM) to calculate the amount of excretal N from grazing livestock deposited on different slope classes throughout New Zealand (MPI, 2021).

Here we examine, for the first time, the predictive performance of the NT model using urine deposition data collected from beef cattle and sheep grazing pastures on complex landscapes. This study uses estimates of urine deposition by beef cattle and sheep grazing on three slope classes. The expectation is that, if available, data other than those used to develop the model (Rowarth, 1987; Sagggar, Mackay, et al., 1990) can be used to explore the robustness of the transfer functions.

2 | MATERIALS AND METHODS

2.1 | NT model

The base NT model uses a mass balance approach to explain the variations in soil P and S found across the three slope classes (LS, MS, HS) in two grazed hill-country pastures (Sagggar, Hedley, et al., 1990; Sagggar, Mackay, et al., 1990b). The updated NT model was extended to include data on the proportion of land in each slope class (LS <12°; MS 12–24°; HS >24°) across the grazed landscape (Sagggar et al., 2015). In this model, the proportion of land in LS (Table 1) and HS

Core Ideas

- The Nutrient Transfer model allocates urine from grazing livestock to different slope classes.
- The predictive ability of the model was explored using urine sensor and tracker data of grazing livestock.
- The model showed a good overall predictive ability for two of the three datasets explored.
- There is a need for more geospatial urine deposition and animal location data on complex land.

(Table 2) classes is used to derive the allocation of urine and feces from grazing livestock to these slope classes. The urine and feces allocation to MS (12–24°) is then calculated by subtracting the LS and HS allocations from the total allocation (Sagggar et al., 2015). The NT model assumes that 61, 30, and 9% of sheep fecal depositions occur on LS, MS, and HS, respectively, for a given range of LS, MS, and HS areas in hill country (Sagggar, Mackay, et al., 1990). Similarly, 55, 31, and 14% of urine depositions occur on LS, MS, and HS areas, respectively (Sagggar, Mackay, et al., 1990).

Values for feces distribution in the NT model (Sagggar et al., 2015) were derived from data collected at Whatawhata in northwest Waikato (Rowarth, 1987), and estimates of urine

TABLE 1 Proportion of livestock urine and feces N allocated to low slope (LS; 0–12°) areas (from Sagggar et al., 2015)

Proportion of land in LS area (L)	Proportion of urine allocated to LS area	Proportion of feces allocated to LS area
$L < 0.01$	$27 \times L$	$30 \times L$
$0.01 \leq L \leq 0.05$	0.27	0.30
$0.05 < L \leq 0.09$	0.405	0.45
$0.09 < L \leq 0.35$	0.55	0.61
$0.35 < L \leq 0.85$	$0.45 \times L + 0.45$	$0.50 \times L + 0.50$
$L > 0.85$	$0.50 \times L + 0.50$	$0.50 \times L + 0.50$

TABLE 2 Proportion of livestock urine and feces N allocated to high slope (HS; >24°) areas (from Sagggar et al., 2015)

Proportion of land in HS area (H)	Proportion of urine allocated to HS area	Proportion of feces allocated to HS area
$H < 0.01$	$10.0 \times H$	$7.5 \times H$
$0.01 \leq H \leq 0.20$	0.10	0.075
$0.20 < H \leq 0.40$	0.14	0.10
$0.40 < H \leq 0.60$	0.21	0.15
$0.60 < H \leq 0.85$	0.28	0.20
$H > 0.85$	$4.80 \times H + 3.80$	$(16 \times H - 13)/3$

distribution (from herbage color effects from urine patches) were derived from data collected at Ballantrae, southern Hawke's Bay (Saggar, Mackay, et al., 1990). The proportion of feces deposited on each slope class (Rowarth, 1987) was relatively constant despite differences in land areas on each slope class, but as the slopes became steeper, the proportion of feces deposited decreased exponentially relative to slope class. The allocation of urine across slope classes in Saggar et al. (2015) was not known. Both of these datasets were gathered from rotationally grazing sheep.

To our knowledge, no published data exist for distributions outside the area range mentioned above (i.e., 9–35% and 24–46% of the total farmlet area in LS and HS, respectively). Outside this range, calculations made in Saggar et al. (2015) have recently been adopted by AIM (MPI, 2021). There is also an underlying assumption that grazing livestock are free to move between slope classes and that the distribution of the slope classes in the grazing area matches the distribution of the slope classes by farm or region.

2.2 | Calculation of N₂O emission factors by excreta form, animal species, and slope class in the AIM

Nitrous oxide emissions from grazing livestock excreta deposited on paddocks have largely been determined from field plot and chamber trials. In the context of this study, and for accounting purposes,

$$EF_3 = \left[\frac{(\text{excreta } N_2O - N - \text{control } N_2O - N)}{\text{excreta } N \text{ applied}} \right] \times 100$$

where EF_3 is the emission factor (N₂O–N emitted as % of excreta N applied), and excreta and control N₂O are the cumulative N₂O emissions from excreta and control plots, respectively (kg N ha⁻¹), relative to excreta N applied (kg N ha⁻¹) (IPCC 2019).

The AIM (MPI, 2021) uses livestock species- and slope class-specific urine EF_3 values based on the meta-analysis of van der Weerden et al. (2020). All dairy cattle urine is assumed to be deposited on flat land (<12°), with an EF_3 value of 0.98%, whereas a slope class- and animal species-urine EF_3 is calculated for beef cattle, sheep, and deer (Table 3).

2.3 | Sources of information for testing the NT model

A literature search on livestock farm systems, grazing, and excretal behavior on simple and complex topographies and N₂O emissions yielded 17 papers of interest, but only five papers had data that justified further interrogation (Betteridge,

TABLE 3 Emission factors (EF_3 ; % of urine N emitted as N₂O–N) by animal species for urine depositions on low slope (LS; <12°), medium slope (MS; 12–24°), and high slope (HS; >24°) areas (MPI, 2021)

Animal species	LS	MS	HS
	%		
Beef cattle	0.98	0.33	0.33
Deer	0.74	0.20	0.20
Sheep	0.50	0.08	0.08

Costall, et al., 2010; Betteridge, Hoogendoorn, et al., 2010; Betteridge et al., 2013; Betteridge et al., 2017; Hoogendoorn et al., 2010).

The development of urine sensor technology to detect urination events (Betteridge, Hoogendoorn, et al., 2010) and the use of satellite tracking technology to locate the grazing animal (Benke et al., 2015) provide new opportunities to record and geo-reference urine deposition across slope gradients. Three datasets were used to test the NT model (Figure 1). Details on animal species and numbers and on the corresponding slope classes, time spent, and number of urinations by livestock on these three sites are provided in Supplemental Figures S1–S3.

Two of the three datasets were collected from field sites that had slope class allocations (i.e., percentage of total area in either LS or HS) that fell outside of the range of slope class allocations (or “boundaries”) used initially to develop the model (Figure 2). The Motere sheep site had a higher percentage of area in LS and a lower percentage of area in HS compared with the Whatawhata farmlets used to develop the NT model. At the Ballantrae site, the area allocation across the LS, MS, and HS classes was 25:34:41, respectively (Figure 2).

2.4 | Impacts on N₂O emissions from sheep, beef cattle, and deer at national scale

In AIM, data on landscape topography (i.e., slope class) and sheep and beef animal numbers on different farm classes are provided by Beef + Lamb New Zealand (2021). The relative area in different slope classes (LS <12°, MS 12–24°, HS >24°) within each farm business class (eight farm classes) and region (17 regions) is estimated from the sheep and beef farm survey and comprises a total area of 7.83 million ha (Table 4). Data collated by the sheep and beef farm survey are relied upon to capture sector-wide changes (e.g., land area changes, livestock species, and livestock numbers) as well as major changes in agricultural management practices. The eight farm business classes (Beef + Lamb New Zealand, 2021) typically represent clusters of farm enterprises

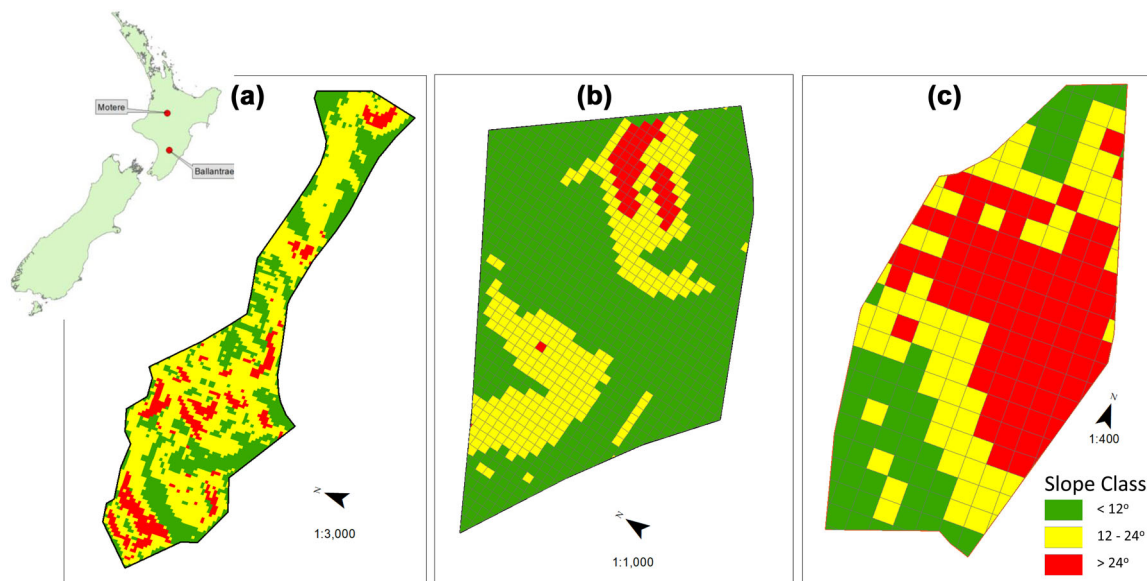


FIGURE 1 Location, scale, and slope classes of the three livestock urine studies used to test the Nutrient Transfer model (Saggar et al., 2015). (a) Beef cattle at Motere farm in central North Island (Motere Cattle), (b) Sheep at Motere farm in central North Island (Motere Sheep), and (c) Sheep at Ballantrae Hill Country Research Station in southern Hawke's Bay (Ballantrae Sheep) (Betteridge, Costall, et al., 2010; Betteridge, Hoogendoorn, et al., 2010; Betteridge et al., 2013, 2017). Slope classes: low slope ($<12^\circ$), medium slope ($12\text{--}24^\circ$), and high slope ($>24^\circ$)

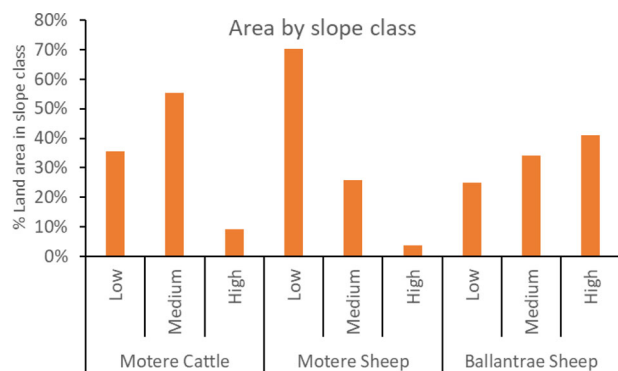


FIGURE 2 Percentage of land area in each of the three slope classes of grazing livestock urine deposition studies (Motere Cattle, Motere Sheep, Ballantrae Sheep) (data from Betteridge, Costall, et al., 2010; Betteridge, Hoogendoorn, et al., 2010, 2013, 2017). Slope classes: low slope ($<12^\circ$), medium slope ($12\text{--}24^\circ$), and high slope ($>24^\circ$)

that have different livestock breeding-to-finishing ratios and proportions of their land in LS, MS, and HS classes (Table 4).

3 | RESULTS

3.1 | Comparison of observed vs. predicted urine deposition across different slope classes

The percentages of urine deposition on LS (Figure 3a) and HS (Figure 3b) areas are shown relative to the land area percent-

ages in each slope class. The Motere Cattle and Motere Sheep sites showed close agreement with the NT model calculations for the amount of urine deposited on LS areas (61 vs. 61% and 74 vs. 77% observed vs. predicted, respectively) (Figure 3a). Overall, the mean absolute error (MAE) between the observed and predicted urine deposition on LS was similar using either the NT model or the assumption that urine deposition is proportional to area (proportional allocation). The NT model slightly overestimated the urine deposition on the HS class at both Motere sites (3 vs. 10% and 2 vs. 10% observed vs. predicted for Motere Cattle and Motere Sheep, respectively) (Figure 3b). For the HS, the assumption of proportional allocation produced a lower MAE than the NT model (0.06 vs. 0.13), suggesting a problem with the allocation between HS and MS in the model. However, because the inventory currently uses the same EF_3 values for MS and HS, this would not make a difference to nationwide estimated N_2O emissions.

The Ballantrae Sheep site had substantially lower estimates of urine deposition on LS areas (21%) compared with the NT model predictions (55%) (Figure 3a). The opposite occurred for sheep urine deposition on HS areas (53 vs. 21%, observed vs. predicted) (Figure 3b), suggesting a low degree of nutrient transfer at the Ballantrae Sheep site.

3.2 | Distribution of slope classes in validation sites compared with nationwide data

The distribution of LS and HS areas at a national scale based on 2018–2019 data is shown in Figure 4. The y-axis is scaled

TABLE 4 Percentage of land area in low slope (LS; <12°), medium slope (MS; 12–24°), and high slope (HS; >24°) for each farm class and region of New Zealand (2018–2019 season; Beef + Lamb New Zealand, 2021)

Farm region	Farm class ^{1a}	Area in LS	Area in MS	Area in HS	Total ha
		%			
Northland, Waikato, Bay of Plenty	3	9.0	44.3	46.7	234,236
Northland, Waikato, Bay of Plenty	4	17.4	56.7	25.9	908,065
Northland, Waikato, Bay of Plenty	5	46.6	53.4	0.0	93,601
East coast	3	7.2	39.3	53.5	482,237
East coast	4	10.1	57.3	32.6	604,355
East coast	5	36.9	54.9	8.2	261,459
Taranaki and Manawatu	3	9.0	23.3	67.7	301,398
Taranaki and Manawatu	4	18.7	40.8	40.5	283,736
Taranaki and Manawatu	5	71.5	28.5	0.0	61,722
Marlborough and Canterbury	1	6.5	33.9	59.6	874,202
Marlborough and Canterbury	2	11.6	17.7	70.7	705,339
Marlborough and Canterbury	6	48.4	41.1	10.5	591,979
Marlborough and Canterbury	8	87.1	12.9	0.0	193,646
Otago and Southland	1	9.9	20.1	70.0	1,033,567
Otago and Southland	2	24.6	40.4	35.1	389,296
Otago and Southland	6	20.9	55.2	23.9	467,103
Otago and Southland	7	58.7	41.3	0.0	347,207

^a1 = South Island high country, 2 = South Island hill country, 3 = North Island hard hill country, 4 = North Island hill country, 5 = North Island finishing, 6 = South Island breeding and finishing, 7 = South Island finishing, 8 = South Island mixed finishing (Beef + Lamb New Zealand, 2021; more information available at <https://beeflambnz.com/data-tools/farm-classes>).

according to estimates of total N excreted within a farm class (prior to allocation to slope classes). Note that the circles in Figure 4 indicate the percentage of LS and HS areas in the five Whatawhata farmlets used to develop the NT model, and the crosses indicate the relative percentages of LS and HS areas from the three sites from which sheep and cattle urine deposition data are available.

Five of the eight farm business classes have a percentage of LS areas that are within $\pm 5\%$ of an experimental site. The three farm business classes outside this range (North Island and South Island Intensive Finishing and South Island mixed finishing) accounted for just under 19% of the estimated total N excreted by sheep, beef, and deer on-farm in 2019. Similarly, five of the eight farm business classes have a percentage of HS areas within $\pm 5\%$ of an experimental site. However, these were not the same five farm business classes as for the LS class. The three farm business classes outside the range for high slopes (South Island High country, South Island Hill country, and North Island Hard hill country) accounted for almost a third of the estimated total N excreted by sheep, beef, and deer on-farm in 2019.

Three scenarios with modifications to the current NT model were assessed, and the implications of using these modified alternatives at national scale were investigated. A modification to the urine deposition on the LS area based on the Motere data (Scenario 1, modified₁ NT model) would lead

to a slight reduction in modeled N₂O emissions from livestock urine. Figure 5a shows a modification of the NT model to allow for the LS urine deposition to match the observed data from the two Motere sites. By using the modified₁ NT model, total annual direct N₂O emissions (i.e., N₂O emissions calculated directly from urinary N) from sheep, beef, and deer urine were 2.82 Gg N₂O–N, compared with 2.84 Gg N₂O–N using the current model, a 0.7% reduction in annual N₂O–N emissions (Figure 5b).

Conversely, modifying the urine deposition on LS areas based on the Ballantrae data (Scenario 2, modified₂ NT model) would lead to a sizeable reduction in modeled N₂O emissions from livestock urine. The modified₂ NT model included a lower urine deposition on LS because the percentage of land in LS areas declined below 35% (Figure 6a). The modified₂ NT model allocated less urine to LS and more to MS, the latter with lower EF₃ values. By using the modified₂ NT model, total annual emissions dropped from 2.84 to 2.24 Gg N₂O–N, a 21% reduction in annual N₂O–N emissions (Figure 6b).

The third scenario replaced the NT model with the assumption of proportional allocation (i.e., a 1:1 ratio of urine deposition/LS area) (Figure 7a). Proportional allocation resulted in a reduction in N₂O emissions from 2.84 to 1.87 Gg N₂O–N, a 34% reduction in annual N₂O–N emissions (Figure 7b).

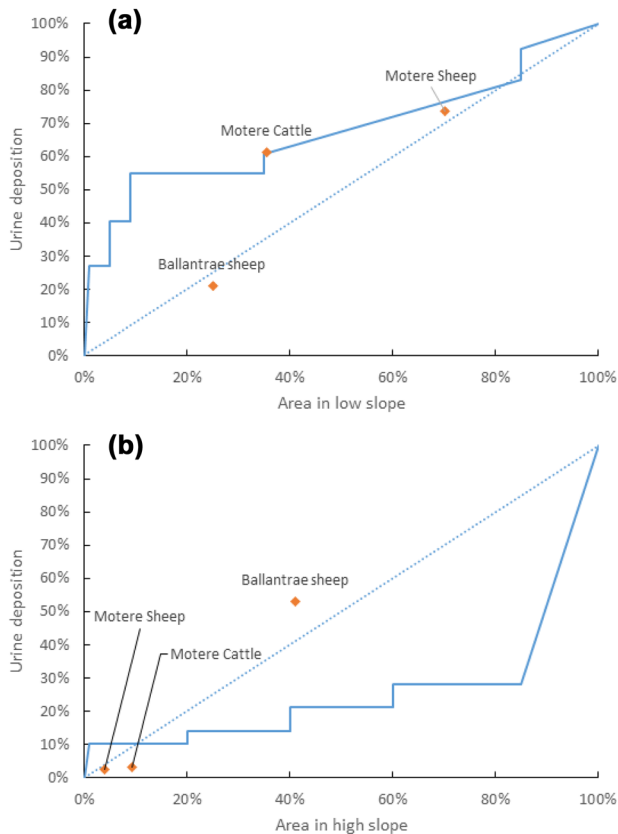


FIGURE 3 Urine deposited on (a) low slope (<12°) class areas and (b) high slope (>24°) class areas. Observed (dots) and predicted (solid line) livestock urine deposition using the Nutrient Transfer model. The dotted line shows the allocation under the assumption of a 1:1 proportion urine deposition/slope area

Another (potential) scenario included modifying the MS and HS urine distribution. However, with the majority of N_2O emissions originating from LS areas (81%), changes to the allocation between MS and HS classes (assuming a lower urine EF_3 is established for HS in the future) could not affect more than the remaining 19% of emissions. Therefore, this scenario was dropped and not examined further.

4 | DISCUSSION

4.1 | Comparison of observed vs. predicted urine deposition across slope classes and implications for nationwide accounting of N_2O emissions

Earlier work using urine sensor technology on complex grazed landscapes focused on identifying critical source areas that could be targeted to improve N_2O mitigation alternatives from livestock urination events and behavior. Examples include the presence of space-planted trees and shade (Betteridge, Costall, et al., 2012), campsite locations (Betteridge, Hoogendoorn, et al., 2010), urination patterns (Betteridge,

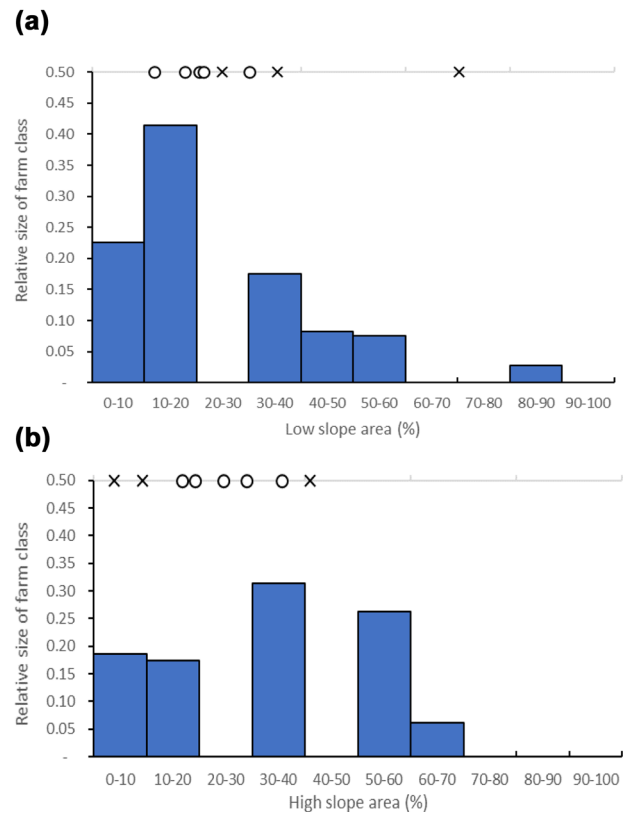


FIGURE 4 The distribution of low slope (LS; <12°) and high slope (HS; >24°) areas at a national scale. Bars show the distribution of areas in (a) LS and (b) HS within New Zealand sheep and beef farm classes (2019 data; provided by the Ministry for Primary Industries). The circles indicate the mean (in %; x axis) of LS and HS areas within each of the five Whatawhata farmlets used to develop the Nutrient Transfer (NT) model. The crosses indicate the mean (in %; x axis) of LS and HS areas within each of the three sites used to test the NT model

Costall, et al., 2010), and grazing behavior (Betteridge, Ganesh, et al., 2012). Although less has been reported on the quantification of ruminant urine deposition on different slope classes or gradients, data collected using novel urine sensor technology linked with GPS collars provide invaluable datasets for assessing assumptions within the methodology for calculation of N_2O emissions from major livestock species (e.g., Misselbrook et al., 2016). Despite a global literature search on grazing livestock excreta on different slopes or gradients, only a few were likely to aid in the assessment of the robustness of the transfer functions (Betteridge, Costall, et al., 2010; Betteridge, Hoogendoorn, et al., 2010; Betteridge et al., 2013, 2017; Hoogendoorn et al., 2010).

In the present study, the amounts of urine deposited on LS areas by beef cattle and sheep at the Motere sites were adequately predicted by the NT model (Figure 3a). The Motere beef cattle allocation of urine on LS areas was the same for both observed and predicted (61%), whereas the observed Motere sheep allocation of urine on LS areas was slightly lower (74%) than the value predicted by the model (77%)

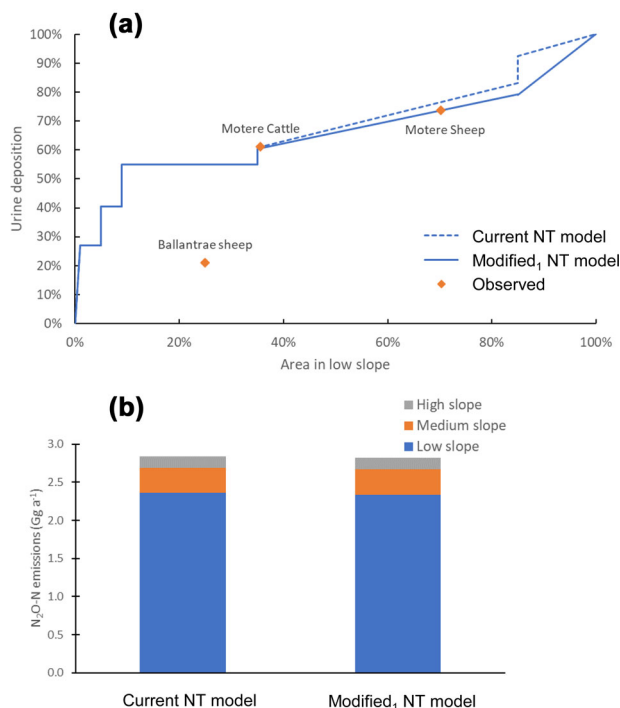


FIGURE 5 (a) Urine deposition on land in the low slope class ($<12^\circ$) using the current vs. a modified₁ Nutrient Transfer (NT) model and (b) 2019 N₂O emissions from beef cattle, sheep, and deer urine calculated using the current vs. a modified₁ NT model (Scenario 1 in the text)

in a site that has a much higher LS/HS ratio (18.2) than the one for cattle (3.9) (Figure 2). Upscaling these Motere sites (modified₁ NT model) only resulted in a 0.7% reduction in direct N₂O emissions at the nationwide level (Figure 5b). Also, on both Motere sites the NT model slightly overestimated the urine deposition on the HS class (Figure 3b). It is impossible to determine the exact reason for this discrepancy or to determine how frequently it might occur at a national scale in the current circumstances. However, with the current AIM using the same EF₃ values for MS and HS classes, the split between urine deposition on the LS class ($<12^\circ$) vs. urine deposition on the MS and HS classes ($>12^\circ$) is what matters for the current calculation of N₂O emissions from New Zealand grazed landscapes. However, if EF₃ values were to be disaggregated by all slope classes and/or slope gradients, more accurate urine deposition data would be required, with a clear understanding of the potential implications from such assumption (i.e., accuracy of N₂O calculations). Although the NT model accurately predicted the percentage of beef cattle and sheep urine deposited on LS areas for the two Motere sites, this was not the case for sheep at the Ballantrae site. Although differences in the allocation between MS and HS would make no difference to the calculated N₂O emissions, changes to the allocation to LS areas have a major impact on calculated N₂O emissions.

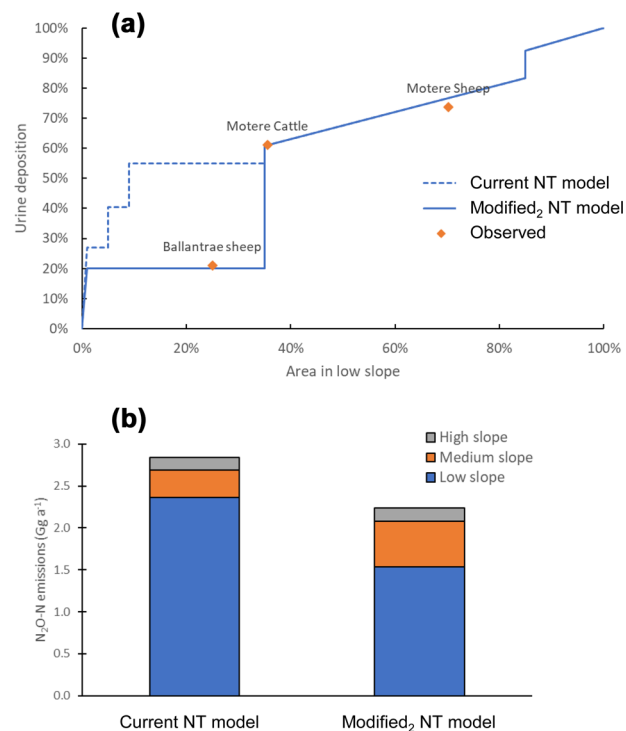


FIGURE 6 (a) Urine deposition on land in the low slope class ($<12^\circ$) using the current vs. a modified₂ Nutrient Transfer (NT) model and (b) 2019 N₂O emissions from beef cattle, sheep, and deer urine calculated using the current vs. a modified₂ NT model (Scenario 2 in the text)

It is interesting to explore some of the possible explanations for the difference in observed vs. predicted sheep urine deposition at the Ballantrae site (with a LS/HS ratio of 0.6), compared with the ability of the NT model to predict urine deposition on LS at the other two sites. The location of areas in different slope classes at the Ballantrae site was such that the two LS areas were at opposite ends of the paddock (Figure 1c), conceivably requiring the animals to spend more time on the steep slope areas while grazing. Further, one LS area was at the bottom of the hill and the other one was at the top. Also, sheep are frequently observed to rest on very small LS areas on stock tracks in MS and HS classes, whereas cattle cannot. Furthermore, the fenced experimental area at Ballantrae was small (0.45 ha) compared with the size of the paddocks used in the Motere Cattle (11.50 ha) and Motere Sheep (2.86 ha) studies. This might have altered the grazing and resting behaviors of sheep when confined to smaller areas. Collectively, these factors may have resulted in a greater percentage of observed urine deposition on HS areas and less deposited on LS areas (Figure 3).

According to the 2019 Inventory figures, 81, 13, and 6% of direct N₂O emissions from sheep, beef, and deer farms originated from LS, MS, and HS classes, respectively. Comparatively, MS and HS slope classes accounted for 21% of

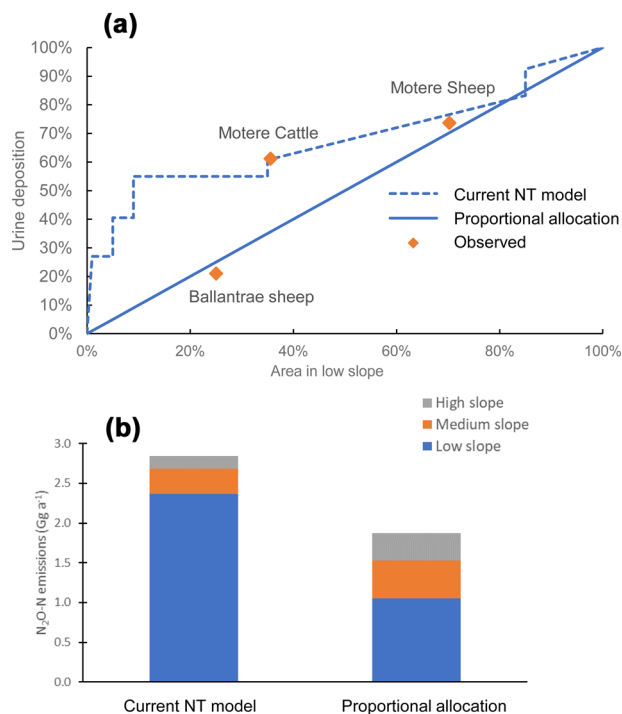


FIGURE 7 (a) Urine deposition on land in the low slope (LS) class ($<12^\circ$) using the current Nutrient Transfer (NT) model vs an assumption of proportional allocation (i.e., a 1:1 ratio of urine deposition/LS area) and (b) 2019 N₂O emissions from beef cattle, sheep, and deer urine calculated using the current NT model vs. proportional allocation (Scenario 3 in the text)

direct N₂O emissions from sheep, beef, and deer, on average for the time period 1990–2012 (Saggar et al., 2015).

Domestic ruminant grazing and excretal behavior data show that livestock excreta is disproportionately deposited on the lower slopes (Betteridge, Hoogendoorn, et al., 2010; Zhong et al., 2016). Although the MAE in urine allocation using the assumption of proportional allocation (1:1 urine deposition/area) performed as well as or better than the current NT model, much of this result was driven by the Ballantrae sheep farm, which had some unusual characteristics. The estimated N₂O emissions are highly sensitive to the amount of urine allocated to LS areas. Therefore, the current NT model (which assumes some animal preference to excrete more on LS areas) represents a more conservative approach to estimating N₂O emissions than proportional allocation.

4.2 | Recommendations for further research

Our study points to the need to collect more geospatial data to better understand the factors affecting animal grazing and excretal behavior and the implications of improved resolution in the description of microtopographies altering the calculation of areas in different slope classes. Limited datasets on urine

deposition across slope gradients are currently available, and this has been identified as an area in need of more work. Based on the analyses conducted here, the current experimental sites do not fully cover the range of slope distributions occurring in New Zealand sheep and beef farms. Farm classes with either a high or low percentage of areas in LS or HS are not well represented in our datasets. In addition to this shortage in data, no quantitative datasets exist on deer excreta deposition on slope gradients.

Grazed hill-country grasslands represent a large source of N₂O emissions. In these landscapes, slope affects grazing and excretal deposition, with disproportionately more livestock excreta deposited on LS, in turn affecting excreta N₂O emissions. Knowledge of spatially diverse EF₃ values can be used to improve estimates of N₂O emissions from complex grazed landscapes in New Zealand (Kelliher et al., 2014; Luo et al., 2013, 2019; van der Weerden et al., 2020) and elsewhere (Chadwick et al., 2018; Gu et al., 2011; Krol et al., 2016; Marsden et al., 2018; Vilain et al., 2010).

The calculations for allocating urine deposition across slope classes (Saggar et al., 2015) entail discrete categories. This means that at certain thresholds or breakpoints in areas in slope classes (e.g., shifting from 4 to 6% of area in LS), the urine deposition changes abruptly. The model predicts a sudden step in urine deposition occurring around specific breakpoints, commonly at 5, 9, and 35% of LS areas. Small changes in land use affecting the proportion of land in LS, MS, or HS classes over time (e.g., commercial forestry or indigenous planting) can potentially result in sudden changes in calculated N₂O emissions between years. Although the greater uncertainty around those specific breakpoints is somewhat diluted when all 17 regional farm classes are considered, it has considerable implications for individual sites and model outcomes, and more research is needed to allow for a smoother transition between these breakpoints. Ideally, sufficient collection of livestock urine and animal location data (i.e., linked to a specific slope) would provide a more continuous dataset to test the NT model in a more comprehensive manner.

Notwithstanding these limitations, this study provides evidence in support of the NT model (Saggar et al., 2015) in its current function at the national level because the model provided suitable predictions of urine deposition in two of the three testing datasets. Unfortunately, given the use of mean urine deposition data (i.e., mean herd or flock behavior and mean values for areas in different slope classes), every new dataset that might offer potential for testing the model's predictive ability accounts for $n = 1$ in the process of testing and validation. Therefore, the need for more excretal behavior data linked to geographic information system tracking (with or without urine sensors; without urine sensors would make trials more affordable) is imperative to attain the empirical continuum mentioned above, especially in view of the strong relationship between the time spent by grazing livestock in a

certain area of the paddock and the number of urination events in that area (Betteridge, Costall, et al., 2010).

Although not identified as a specific focus of the current study, with the emergence of remote sensing technologies that can provide an estimate of the protein concentration of pastures in situ, the opportunity exists to estimate the N concentration of pasture as a landscape, rather than a land use, attribute. In situ N concentration could replace static N concentration values used for cattle and sheep, thus providing more accurate partitioning of excreta N into urine and dung, which would improve farm-scale and national-scale GHG reporting. The increasing availability of higher-resolution land resource information through LIDAR and other technologies provides digital elevation models that enable slopes and areas to be better defined across landscapes. If coupled with improvements in satellite tracking technology that brings greater precision to the location of the grazing animal, the new datasets will enable modeling emissions beyond broad slope classes.

The current study is based on the distribution of urine patches deposited across slope classes but has not considered possible differences in N loadings between patches. Although there is limited 24-h data showing high variability in urinary N concentration among animals within days and between days, there is clear evidence that urine excreted around sunrise is more concentrated than at other times of the day (Betteridge et al., 1986, 2013). These events relate to where the animals camp overnight. Thus, N loads in campsite urine patches are likely to greatly exceed loads in urine patches excreted at other times of the day when animals are typically grazing on MS and HS areas in hill country. The NT model and N₂O emission estimates could be strongly influenced by where animals rest and ruminate. Therefore, a future refinement would be to investigate whether the distribution of urine-N between slope classes matches the distribution of urine patch deposition. Except indirectly via the different EF₃ used for different animal species, the current emission factor approach neglects any N loading effect on N₂O emissions. Currently, there is a shortage of experimental evidence for an N loading effect on emissions to justify changing the emission factor methodology. If the approach were to be changed, obtaining adequate estimates of the distribution of N loadings at a national level would pose an additional challenge to AIM, but limited data currently exist to underpin such an approach.

5 | CONCLUSIONS

The NT model showed a good overall predictive ability (i.e., predictions were considered suitable compared with estimates obtained in the field or observed data) for two of the three datasets. For all three datasets, there were differences (observed vs. predicted) in urine deposition on MS and HS

areas. The five farmlets used to develop the model and the three urine deposition datasets used to test the NT model do not cover the full range of slope profiles in New Zealand. Farm Production Regions with disproportionate areas in low slope or high slope are not well represented. We have identified the need for more geospatial urine deposition data from landscapes that are topographically out of the range from which the model was developed, particularly on urine deposition on medium and high slopes, ideally providing livestock urine deposition along a continuum rather than discrete areas in different slope classes.

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AUTHOR CONTRIBUTIONS

Ronaldo Vibart: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Writing – original draft. Donna Giltrap: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing – review & editing. Surinder Saggat: Conceptualization; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing – review & editing. Alec Mackay: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Writing – review & editing. Keith Betteridge: Data curation; Resources; Writing – review & editing. Des Costall: Data curation; Resources. Mike Rollo: Methodology; Writing – review & editing. Ina Draganova: Data curation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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