Examining the New Zealand methane emissions dataset to obtain updated predictions of methane emissions from sheep suitable for incorporation into the national greenhouse gas inventory

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Introduction

Agriculture in New Zealand is the single largest source of greenhouse gas (GHG) emissions, representing 48.4% of all CO_2-equivlent emissions. Enteric methane (CH_4) emissions from ruminants, predominately sheep and cattle, account for two-thirds of agricultural GHG emissions (MfE, 2015). New Zealand is required, as are all Annex 1 parties, to report its emissions using guidelines outlined by the International Panel on Climate Change (IPCC) (IPCC 1996, IPCC 2000 and IPCC 2006). It is important that enteric CH_4 emissions from ruminant livestock are reported as accurately as possible. To estimate enteric CH_4 emissions from sheep, New Zealand uses an IPCC Tier 2/3 approach which comprises detailed population, performance and feed characterisation, the estimation of dry matter intake (DMI) for each category of animal using the Australian Feeding Standards, and New Zealand developed emissions factors that relate CH_4 emissions to DMI (e.g. CH_4 yield (Ym) = 20.9 g CH_4 kg DMI^{-1}). This country specific methodology ensures that the unique features of New Zealand agriculture are taken into account when estimating emissions.

Predicting methane from dry matter intake

Muetzel and Clark 2015 dataset and algorithms

When estimating enteric CH_4 emissions from cattle and sheep, New Zealand uses a CH_4 yield factor multiplied by an estimated value for daily DMI. For sheep, two Ym values are used depending upon sheep age; for sheep >1 year of age the value is 20.9 g CH_4 kg DMI^{-1} and for sheep <1 year it is 20% lower at 16.8 g CH_4 kg DMI^{-1}. These values were generated from an analysis of experiments conducted prior to 2004 with many of these experiments being with grazing animals where both the CH_4 emissions and the DMI were estimated using indirect methods, such as the sulphur hexafluoride tracer technique for CH_4 combined with faecal collection and diet digestibility estimation for DMI (Clark et al 2003).

To help develop more robust emission factors for sheep the New Zealand Ministry for Primary Industries (MPI) funded a series of four experiments where emissions from sheep fed pasture of differing quality at various feeding levels were measured (Muetzel & Clark 2015). To decrease the uncertainty stemming from the techniques used previously, CH_4 emissions were measured in respiration chambers and DMI was controlled and measured accurately.

Results from this series of experiments (see Muetzel and Clark 2015 for full details) showed that for the entire dataset (510 measurements from 115 animals), DMI explained most of the variation of CH_4 production per animal per day (pCH_4, g/d) and if a single CH_4 emissions was to be used they could best be estimated from the following equation

(Eq.1) All Sheep; $\ln(pCH_4) = 0.792\ln(DMI) + 3.1$

As the intercept is different from zero, this indicates that using a constant yield factor Ym is inadequate when predicting CH_4 since estimated CH_4 emissions per kg DMI^{-} depend to some extent upon DMI itself as emissions per unit of intake go down as intake increases. A non-zero intercept for CH_4 emission from sheep has been reported elsewhere (Hammond et al 2013)

Results from an analysis of the entire data set also indicated that diet quality and animal age in general had a minor effect on pCH_4. Assessing the effect of age on CH_4 emissions was however hindered by the narrow range of ages used in the study and so the dataset was separated into sheep <1y and sheep >1y of age and analysed separately. It can be argued that this separation is somewhat arbitrary as it is unlikely that there is a sharp change in emissions at a particular age, but previous analysis has shown differences in emissions from these categories of sheep (Lassey references from IPCC). Currently the IPCC, based upon New Zealand data, recommend separate CH_4 emissions factors for sheep based on age (<1 and >1) (IPCC 2006). In addition accurately estimating emissions from younger sheep is important since large numbers of sheep are slaughtered before they reach 1 year of age; in the twelve months from October 1 2013 to 30 September 2014, more than 20 million sheep in New Zealand were slaughtered before they reach 1 year of age (B+LNZ, 2015). When analysed as two separate data sets the best methane predictive equations for old and young animals (pCH_4, g/d) are given below in equations 2 and 3.

(Eq.2) Sheep >1y; $\ln(pCH_4) = 0.826\ln(DMI) + 3.15$

(Eq.3) Sheep <1y; $\ln(pCH_4) = 0.749\ln(DMI) + 0.051ME + 2.45$

The most notable feature of this separate analysis was that for young animals only, metabolisable energy content (ME; MJ/kg DM) of the diet had a significant effect on predicted emissions in addition to dry matter. These data therefore support the hypothesis that emissions from young sheep are different to those from older sheep. However, based on these relationships the difference cannot be quantified by simply assuming a constant lower Ym, as is done currently in the national inventory, since it is dependent upon both DMI and ME, both of which change monthly in the New Zealand inventory.

Additional dataset

Although the Muetzel and Clark (2015) analysis was based on 510 measurements from 115 sheep (termed the original dataset from now on) it was recognised that additional CH_4 data from animals fed fresh cut pasture in New Zealand were available to supplement their dataset. These additional data were collated and analysed separately, and in conjunction with the original dataset, with the aim of obtaining definitive CH_4 prediction equations suitable for inclusion in the New Zealand national agricultural inventory based on all currently available suitable information.

For inclusion in the additional dataset two criteria were applied (1) the diet had to comprise fresh cut grass dominated pasture and (2) CH_4 measurements had to be made in respirations chambers for a minimum of 48 h. This resulted in a total of 306 measurements of CH_4 emissions from 289 animals. These data were collected from 20 measurement periods in 14 different experiments carried out from 2009 to 2015. All measurements were conducted at the New Zealand Ruminant Methane Measurement Centre, Palmerston North; a list of the experiments is given in Table S1 at the end of this report. Data on ME were only available for 174 measurements from 174 sheep and to remain consistent with the original dataset the additional dataset was reduced to 174 animals when analysing the influence of variables other than DMI on methane emissions. If ME was found to have no significant effect, these unused data without ME were reintroduced into the analysis.

Statistical analysis

Data from (Muetzel and Clark (2015) named the 'original' and the newly collated data (named the 'additional' for ease of description) were first analysed using simple linear regression with pCH_4 as the independent variable and DMI as the explanatory variable. The datasets were then compared using the REML method of GenStat Version 13 (Payne et al. 2009), with the fixed effect of dataset and random effects including experiment, experiment x experimental period and experiment x sheep, to explore whether predicted means of animal and dietary components differed; a significant difference was declared if $P< 0.05$.

The new combined dataset (original plus additional) was then used to obtain updated methane prediction algorithms. When analysing the whole dataset the response variables (pCH_4) and the dominant explanatory covariate (DMI) needed to be transformed using natural logarithms in order to de-trend the residuals, linearize, and stabilize variances.

When analysing the combined dataset age was not used as an exploratory variable alongside other variables such as DMI due to the limited range of ages used in the trials; range 0.3 – 3.0 years. An approach consistent with the analysis by Muetzel & Clark (2015) was taken, with data from young (<1) and old (>1) animals being analysed separately. For the combined dataset analyses were performed using a linear mixed effects model and the REML method of GenStat Version 13 (Payne et al. 2009).

To compare the algorithms obtained by Muetzel & Clark (2015), and those obtained from the combined dataset, against actual pCH_4 measurements Lin's concordance correlation coefficient (Lin 1998) was used. This coefficient measures how well a set of observations are able to reproduce an original set of measurements. Values of ±1 denote perfect concordance and discordance; a value of zero denotes a complete absence of concordance. A significant difference in concordances ($P < 0.05$) was declared if the confidence intervals did not overlap (Payne et al. 2009).

Comparison of datasets

The first objective of this study was to determine if the two datasets, original and additional differed. A visual comparison of the additional and the original datasets is given in Figure 1, while Table 1 shows descriptors of animals and diets fed to sheep within each dataset. Age structure and live weight of animals in the two datasets were similar. No difference in DMI and pCH_4 was observed, but the observed mean Ym of sheep in the additional dataset was 5.6% lower ($P = 0.040$). Significant differences in diet composition between the datasets were limited to a higher ash content in the additional dataset ($P = 0.018$).

A simple linear regression between DMI and pCH_4 (Figure 2) showed that the additional dataset is more variable with 69% of the pCH_4 being explained by DMI as compared to 80% in the original data set. The additional dataset regression equation had a higher intercept ($P = 0.016$) than the original dataset but the slopes of the two regression lines were not significantly different ($P = 0.129$). This difference in the strength of the relationship between pCH_4 and DMI between datasets may in part be explained by the fact that the additional dataset was constructed from multiple experiments (n = 20) over a six year period with variable numbers of sheep (6-24) fed pasture, while the original data set was obtained from a four highly targeted and controlled experiments. Both datasets however are consistent with the common finding that DMI is the biggest determinant of CH_4 emissions from ruminants (Reynolds et al 2011, Hammond et al 2013).

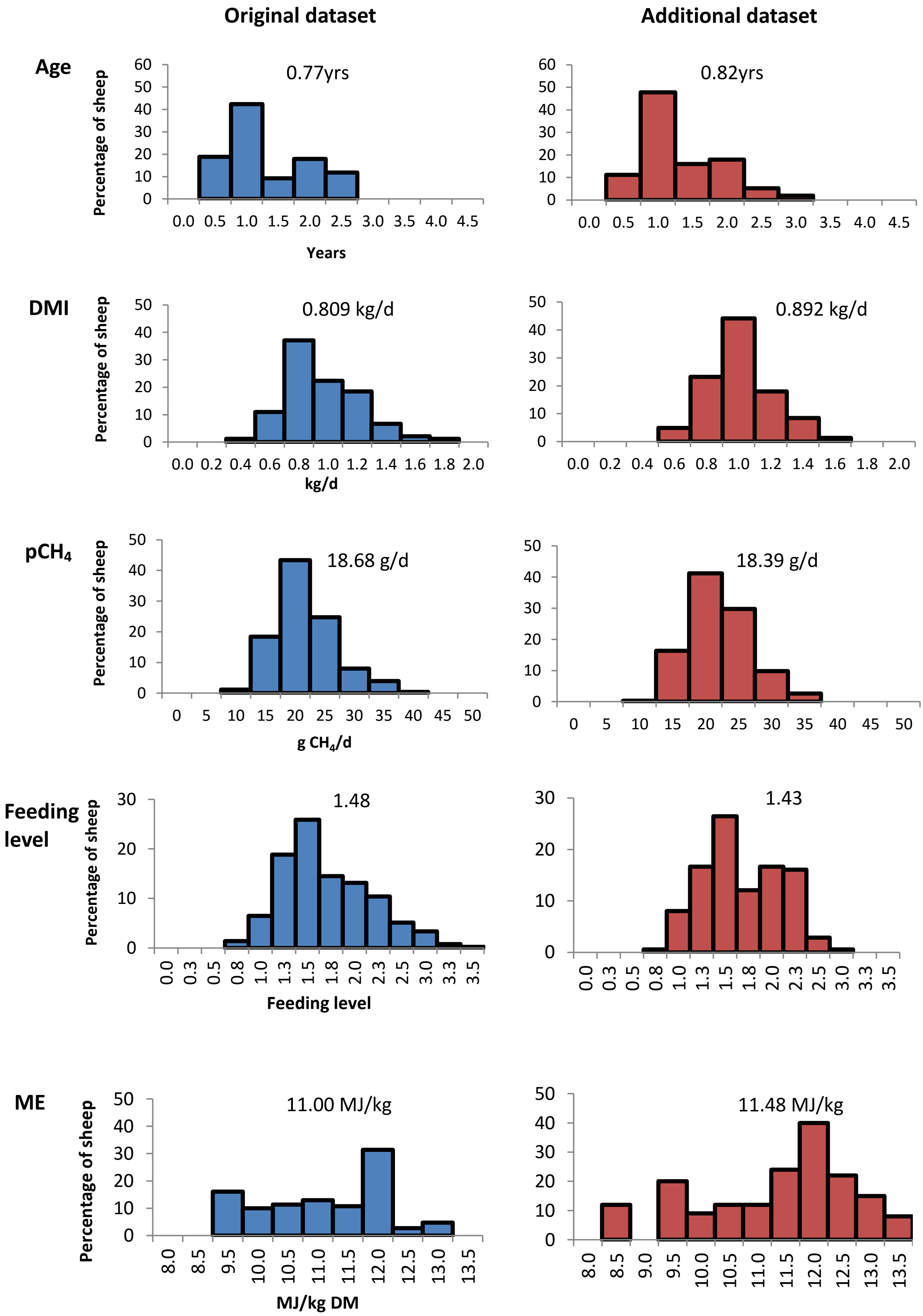

Figure 1 Histogram showing the spread of the data and median value in the original and additional datasets for sheep age, dry matter intake (DMI), methane production (pCH_4, g/d), feeding level achieved maintenance energy requirements and metabolisable energy (ME, MJ/kg) content of the

diet. Sheep in age categories 0.5 and 1.0 were <1 year of age. Those in categories 1.5 and above were >1 year of age.

Given the broad similarity between the two datasets in terms of both animal and dietary characteristics, and in the underlying relationship between DMI and pCH_4, it was deemed appropriate to combine the data and analyse as a single dataset.

Table 1 Summary of the chemical composition, organic matter digestibility (OMD), digestible organic matter intake (DOMI), metabolisable energy (ME) content of pasture fed and animal age, live weight, dry matter intake (DMI) and methane production (pCH_4) and yield (Ym) of sheep within the Original (n = 510) and Additional datasets (n = 306).

Parameter	Original	Additional	SED	P-value
Age (years)	1.6	1.2	0.217	0.750
Live weight (kg)	41.8	43.9	2.274	0.369
DMI (g/d)	0.86	0.93	0.048	0.210
DOMI (g/d)[2]	0.63	0.72	0.048	0.085
mMEr[1]	1.56	1.63	0.116	0.536
CH_4p (g/d)	19.6	19.8	1.124	0.839
Ym (g/kg DMI)	23.0	21.7	0.594	0.040
Ash (g/kg)	81.7	97.6	6.43	0.018
CP (g/kg)[1]	145.3	164.1	12.27	0.134
NDF(g/kg)[1]	505.2	488.6	24.27	0.498
SSS (g/kg)[1,2]	127.4	122.5	15.12	0.746
Lipid (g/kg)	26.0	29.9	2.07	0.066
OMD (g/kg)[2]	736.0	768.6	30.36	0.292
ME (MJ/kg)[2]	11.0	11.3	0.41	0.505

[1]mMEr, achieved feeding level for maintenance energy requirements; CP, crude protein; NDF, neutral detergent fibre; SSS, soluble sugars and starch.
[2]n = 174, NIRS analysis of diet offered.

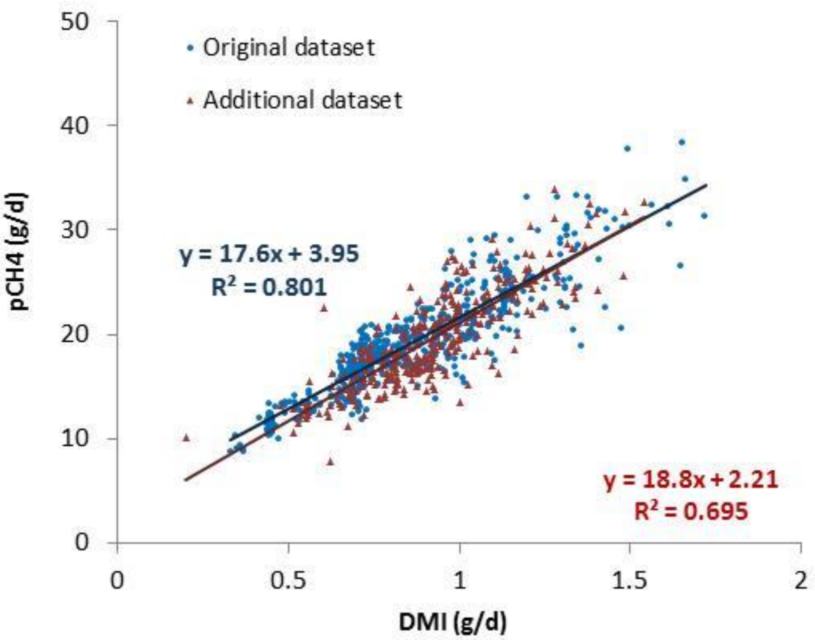

Figure 2 Linear regression of methane (pCH_4, g/d) production measured and dry matter intake (DMI, kg/d) for the original (n = 510) and additional (n = 307) datasets.

Analysis of the combined dataset

Updated methane prediction algorithms

The combined dataset (n = 815) was analysed by REML analysis with DMI as the sole explanatory variable for pCH_4 (g/d) (Equation 4).

(Eq.4) All Sheep; $\ln(pCH_4) = 0.763\ln(DMI) + 3.039$

This analysis confirmed that for sheep fed pasture dominated diets, DMI alone is a good predictor of methane emissions per animal. When analysed by REML analysis the inclusion of feed characteristics as additional explanatory variables (e.g. ME, Digestibility, Fibre etc.) did not significantly impact on the relationship between pCH_4 and DMI. Equation 4, which is obtained from an analysis of the combined dataset, has a numerically lower slope but similar intercept to Equation 1 derived from the original dataset and hence predicted CH_4 values are slightly lower than values predicted by the original dataset, particularly at higher levels of intake (Figure 3).

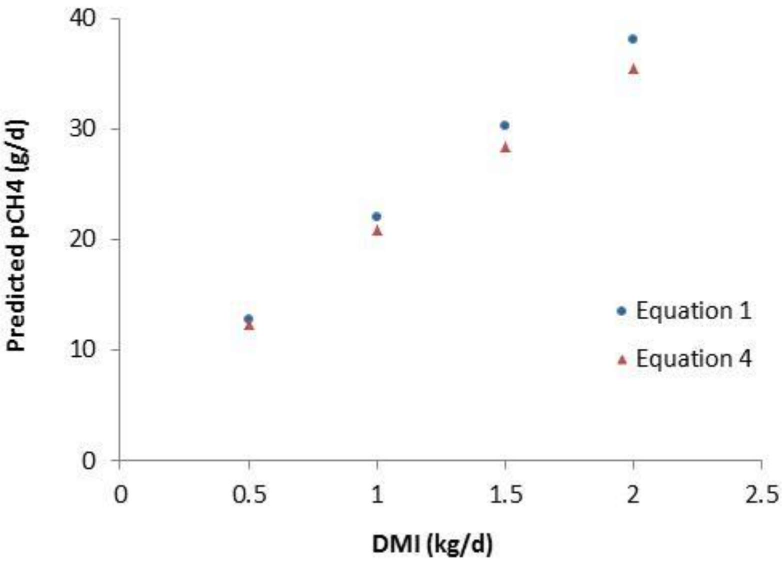

Figure 3 Predicted methane production (pCH_4) using dry matter intake (DMI) where Equation 1 is based on data from the original dataset or Equation 4 based on data from the combined dataset.

The analysis of the Combined dataset also indicated that age ($P<.001$) had a significant impact on the relationship between pCH_4 and DMI but the limited range of ages in the dataset precluded the use of age as an explanatory variable. In line with the approach adopted by Muetzel & Clark (2015) the combined dataset was split by age, with one set representing sheep >1 year and the other sheep <1 year. As observed for the original dataset, in sheep >1 year dietary ME did not have a significant effect on the relationship between pCH_4 and DMI (P = 0.399), Equation 5, whereas ME did impact on this relationship for sheep <1 year (P <.001, Equation 6). The range of feed ME values for young (8.5-12.2 MJ/kg DM) and old (8.5-13.1) sheep were very similar.

Equation 5 (sheep > 1 yr) $\ln(pCH_4) = 0.765\ln(DMI) + 3.09$ (n= 323)

Equation 6 (sheep <1 yr) $\ln(pCH_4) = 0.734\ln(DMI) + 0.05(ME) + 2.46$ (n=386)

The updated equation for sheep >1 (Equation 5), obtained from splitting the combined dataset by age, resulted in predicted CH_4 emissions (Figure 4) being lower than in the corresponding equation obtained from the original dataset (Equation 2), particularly at higher levels of intake. In contrast, Figure 5 shows that predicted emissions for sheep <1 from the age split combined dataset (Equation 6) were almost identical to those obtained from the age split original dataset (Equation 3), irrespective of ME concentration of the diet and DMI.

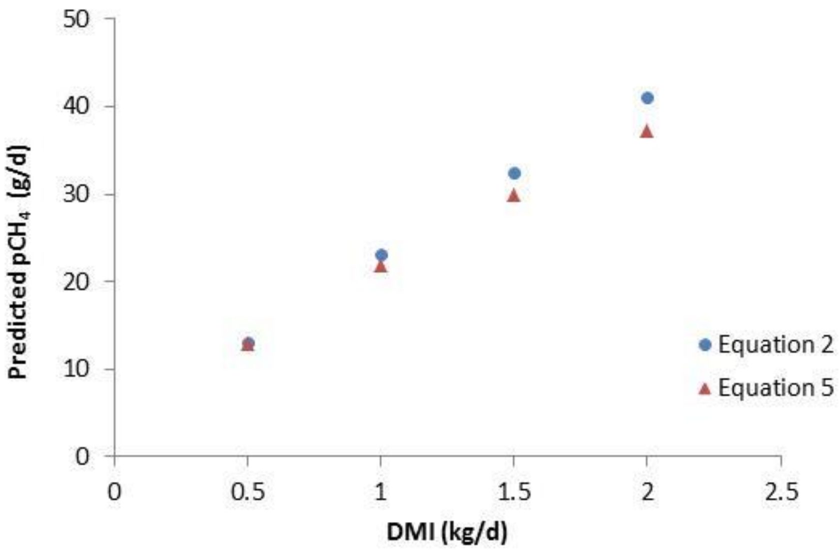

Figure 4 Predicted methane production (pCH_4, g/d) modelled with increasing dry matter intake (DMI) for sheep >1 year based on the Original dataset (Equation 2) or the Combined dataset (Equation 5).

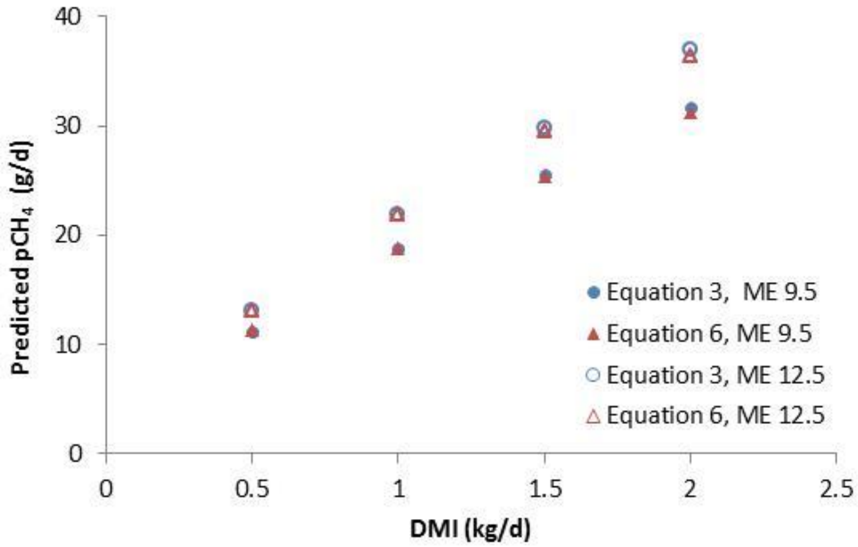

Figure 5 Predicted methane production (pCH_4, g/d) modelled with increasing dry matter intake (DMI) for sheep <1 year based on the Original dataset (Equation 3) or the Combined dataset (Equation 6) for diets of differing metabolisable energy (ME, MJ/kg dry matter).

Which algorithms should be used in the national inventory?

The combined dataset contains all current New Zealand data on methane emissions measured from New Zealand sheep fed fresh grass-dominated diets where emissions were measured using methane respiration chambers and where intake was accurately measured. An analysis of this database can therefore provide robust methane prediction algorithms for use in the New Zealand national agricultural methane inventory. However, the analyses presented above show that there is a choice with respect to which algorithms can be used.

Dry matter intake is the major determinant of enteric CH_4 emissions and a single equation (Equation 4) using DMI alone can be used to predict emissions (g CH_4/sheep/day). This relationship explains 76% of the variation in emissions, a value that is consistent with other published data (Clapperton & Blaxter 1965, Hammond et al 2009, 2013, Reynolds et al 2011). If a simple approach is required, one that does not need to take into account such factors as age and diet quality, the use of equation 4 can be justified. However, since the analysis undertaken here indicates that for young animals an additional variable can improve predictions the use of separate equations for sheep >1 and sheep <1 needs to be considered.

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One method for assessing the fit of a model to data is to use a concordance analysis. This is presented in Table 3.

Table 3 Lin's concordance of equations based on dry matter intake (DMI, equation 1 and 4) or age (equation 2 and 3 applied to sheep >1 year, n=323, or equation 3 and 6 sheep <1 year of age, n=386) as applied to the combined dataset for the prediction of methane production (g/d) and compared with respiration chamber measurements. Significant differences can be declared if confidence intervals do not overlap (P<0.05)

Equations	n	Concordance	95% CI	
			Lower	Upper
DMI				
1[1]	816	0.8585	0.8401	0.8749
4[2]	816	0.8464	0.8277	0.8631
Age				
2/3[1]	709[3]	0.9155	0.9029	0.9265
5/6[2,3]	709[3]	0.8975	0.8839	0.9097

[1]Equations derived from the original dataset.
[2]Equations derived from the combined dataset.
[3]Sheep <1year without ME for diet offered were not included

This analysis shows that when applied to the original and combined datasets and compared against respiration chamber CH_4 measurements, equations 1-6 all have high predictive values (i.e. Concordance values > 0.8) for pCH_4. In addition, the age separated equations (2/3 and 5/6) show significantly higher concordance than the single equations (1 or 4) based solely on intake. This means that age separated equations are better able to predict the datasets from which they are derived than a single equation applied to the whole dataset. This applies both to the original and combined datasets. Therefore the use of a single equation for all sheep using DMI as the sole explanatory variable is not appropriate if age and ME data are available. Since the New Zealand Tier 2/3 agricultural inventory methodology does divide animals into age classes (<1 and >1), and explicitly uses ME for calculating DMI, it would therefore seem appropriate that if new CH_4 prediction algorithms are to be adopted for use in the national inventory they should be equations 5 & 6.

Equation 5 (sheep > 1 yr) $\ln(pCH_4) = 0.765\ln(DMI) + 3.09$

Equation 6 (sheep <1 yr) $\ln(pCH_4) = 0.734\ln(DMI) + 0.05(ME) +2.46$

Impact of the updated algorithms on predicted methane emissions

To quantify the impact these new recommended CH_4 prediction equations have on estimated emissions from New Zealand sheep, emissions from sheep >1 and sheep <1 were estimated for the years 1990 and 2012 using the national agricultural inventory accounting software. The age specific equations, Equations 5 and 6, were used separately to estimate emissions for ewes and lambs and compared with (a) emissions obtained using a single equation, Equation 4, and (b) estimated obtained using the current Ym values of 20.9 g/kg DMI for ewes and 16.8 g/kg for lambs. Estimates of emissions were calculated per animal, either per day or per year (Table 4 & 5), and annual emissions for ewes and lambs (Table 6) or all sheep combined (Table 7).

Emissions per animal

Emissions per animal per day

The impact of the new equations on an individual animal per day (i.e. pCH_4) varies depending on the equations used (Table 4).

Table 4 A comparison of methane production (g/d) obtained using equations the combined dataset at varying levels of dry matter intakes (DMI, kg/d) and dietary metabolisable energy (ME, MJ/kg), or using the current New Zealand Greenhouse Gas Inventory methane yield factors (Ym, g CH_4/kg DMI).
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	DMI											
	0.5 (kg/d)			1.0 (kg/d)			1.5 (kg/d)			2.0 (kg/d)		
Ym factor												
Ym (>1 yr)		10.5			20.9			31.4			41.8	
Ym (<1 yr)		8.4			16.8			25.2			33.6	
Equations												
Eq. 4 (All)		12.3			20.9			28.4			35.4	
Eq. 5 (>1 yr)		12.9			21.9			29.9			37.2	
ME (MJ/kg DM)[1]	9.5	11	12.5	9.5	11	12.5	9.5	11	12.5	9.5	11	12.5
Eq. 6 (<1 yr)	11.3	12.2	13.2	18.8	20.3	21.9	25.4	27.3	29.5	31.3	33.7	36.4

[1]Different levels of dietary metabolisable energy (MJ/kg DM) for each level of intake for calculating predicted pCH_4 using Equation 6.

The use of a single equation (Equation 4) to predict emissions resulted in values that were always higher than those predicted by the Ym value for sheep <1. For sheep>1 the predicted values were higher at an intake of < 1kg/day but were lower when the intake increased above 1 kg/day. This confirms the ability of the equations to capture the commonly found negative relationship between methane yield and increasing intake (Clapperton & Blaxter 1965, Hammond et al 2013), the biology of which is unable to be captured by the use of a single constant Ym value.

Equation 5, the recommended equation for sheep >1, predicted higher daily emissions for intakes of 0.5 and 1kg/head/day but lower values at intakes of >1.5kg/day. Since equation 6, the recommended equation for sheep <1 has an ME component, any comparisons have to take this into account. At all levels of intake, predicted emissions rise as ME increases, and at all levels of intake and ME concentration emissions from sheep <1 predicted by equation 6 are higher than those predicted using the current inventory Ym for sheep <1.

The use of age specific equations (Equations 5 and 6) to predict pCH_4 does not support the consistent 20% difference between sheep <1 year and >1 year of age using the current Ym values. Instead, when sheep <1 year consumed a diet with an ME of 11 MJ/kg DM at an intake level of 0.5 and 1 kg DM/d, pCH_4 ranged from being 5.4% to 7.6% lower than sheep >1 year of age, respectively. Across all intake levels the difference between young and old sheep was increased when the diet of was of lower quality, but almost disappeared if sheep were fed a high quality diet of 12.5 ME MJ/d.

Emissions per animal per year

The estimated annual CH_4 emissions per sheep using the new recommended prediction equations or current Ym factors are compared in Table 5 for the years 1990 and 2012. The impact of age specific equations to predict the CH_4 emissions of a sheep >1 year in 1990 (equation 5) had little effect on annual emissions per animal, but resulted in a 24.6% (3.46-4.31 kg CH_4/year) increase above current emissions from sheep <1 year of age (equation 6). This increased to 40.4% (4.84 kg CH_4/year) when Equation 4, the single sheep equation, was used. In contrast, the use of equation 4, the single sheep equation, resulted in an emission reduction of 5.5% for a sheep >1year of age. Values for 2012 followed a similar trend with the use of the updated equations resulting in a fall in estimated emissions from sheep >1 and a rise in estimated emissions from sheep <1. It should be noted that because performance characteristics which affect intake change over time (e.g. liveweight, liveweight gain, lambing % and weight at slaughter) using updated algorithms also has an impact on the changes in estimated emissions over time; this is especially notable for sheep >1 where the updated algorithms result in a smaller increase in estimated emissions per head between 1990 and 2012.

Table 5 Calculated methane emissions (kg CH_4) per animal per year for sheep in 1990 or 2012 using current methodology from the national greenhouse gas inventory or calculated using a single equation for all sheep (Equation 4) or age specific equations (Equations 5 & 6)

	Sheep>1			Sheep<1		
	Current Ym	Eq. 5	Eq. 4	Current Ym	Eq. 6	Eq. 4

1990	9.40	9.37	8.90	3.46	4.31	4.84
2012	11.12	10.65	10.11	4.81	5.54	6.34
Change	1.72	1.28	1.21	1.35	1.23	1.5

National emissions

Total estimated national emissions for sheep >1 and sheep <1 for 1990 and 2012 are represented in Table 6.

The impact of the new equations on total CH_4 emissions followed a similar trend to the annual emissions per head. In 1990 estimated emissions from sheep >1 year were reduced by 0 to 5.3% and by 4.3 to 9.1% in 2012 using either the age specific or single equation, respectively, when compared with the current method. In contrast, in 1990, estimated emissions from sheep <1 year are noticeably higher (20.0 to 36.7%) than those estimated using the current method, although in 2012 this increase was smaller; 10.8 to 28.2% using the age specific or single equations respectively. The use of the age separated equation, equation 5, in sheep>1 resulted in the largest fall in emissions between 1990 and 2012 compared with either the current method or the updated single sheep equation. The use of either of the updated equations resulted in a greater fall in estimated emissions than the current inventory method.

Table 6 Annual methane emissions (t CH_4) from ewes and lambs in 1990 or 2012 calculated using current methodology from the national greenhouse gas inventory or calculated using a single equation for all sheep (Equation 4) or age specific equations (Equations 5 & 6)

	Sheep>1			Sheep<1		
	Current	Eq. 5	Eq. 4	Current	Eq. 6	Eq. 4
1990	391,118	390,004	370,449	64,402	77,268	88,039
2012	230,129	220,281	209,164	58,866	65,219	75,463
Change	-160,989	-169,723	-161,286	-5,536	-12,049	-12,576

Compared with the current method the use of a single equation for all sheep made little difference to the estimated total combined ewe and lamb emissions in 1990, whilst total emissions were 2.5% higher when using the age specific equations (Table 7). However, in 2012 the total combined ewe and lamb emissions decreased by just over 1% compared with the current method using either of the updated equations. The estimated fall in emission over time was 15,247 and 7,336 t CH_4 respectively greater using the age related equations and the updated single sheep equation than the current inventory method.

Table 7 Total combined annual methane emissions (t CH_4) from ewes and lambs in 1990 or 2012 calculated using current methodology from the national greenhouse gas inventory or calculated using a single equation for all sheep (Equation 4) or age specific equations (Equations 5 & 6).

	Current	Eq. 5 & 6	Eq. 4
1990	455,520.49	467,272.12	458,487.92
2012	288,995.53	285,499.77	284,626.73
Change	-166,525	-181,772	-173,861

These calculations, undertaken using the national inventory software, clearly demonstrate that the new equations obtained from the combined dataset presented here have an impact upon New Zealand's estimated annual CH_4 emissions. In summary, the use of the age related equations obtained from the full New Zealand dataset results in slightly higher estimated CH_4 emissions in 1990, but, because of lower emissions in 2012, leads to the greatest reduction in emissions (181,772 t CH_4 (38.9%) compared with 166,252 t CH_4 (36.5%) using the current fixed Ym values). The use of a single equation had little impact on emissions in 1990, but reduced emissions below the current methodology in 2012. This results in a fall of CH_4 emissions of 173,861 t, which is midway between the current methodology and the age related equations.

The increase of emissions in 1990 is largely driven by the new age related equations not supporting a consistent 20% difference in emissions between sheep <1 or >1 year of age. However, despite this, both the single equation (Equation 4) and the age related equations (Equation 5 & 6) resulted in a greater reduction of total annul emissions from 1990 to 2012 than current methodology. This occurred because the new equations are better able to capture the negative relationship between increasing DMI and decreasing CH_4 per kg of DMI (Blaxter & Clapperton 1965), therefore recognising improvements in animal performance and the higher levels of feed intake found in New Zealand sheep over this time period (MfE 2014).

Conclusion

The sourcing of additional data from experiments measuring CH_4 emissions in New Zealand conducted between 2009 and 2015 to add to those analysed by Muetzel & Clark (2015) confirmed that the relationship between pCH_4 and DMI was influenced by the ME of the diet for sheep <1 , but not for sheep >1 year of age. Compared to the original dataset the difference between estimated emissions from young and old animals decreased when the additional data were added. The concordance of pCH_4 was high both for a single sheep equation and separated age related equations but the separation of sheep by age significantly improved the concordance between predicted and measured emissions. We recommend that the two age related equations obtained from the combined dataset should be adopted for use in the New Zealand national sheep industry as they are sourced from New Zealand measurements, undertaken across a broad range of diet quality and sourced from experiments where both intake and CH4 emissions were measured accurately. With regard to the effects of age on emissions the available data do not span the full range of ages found in practice and hence no attempt was made to treat age as a continuous variable in the analysis. Biologically it is difficult to envisage a sharp cut off point at which emissions begin to diverge but data limitations preclude any more detailed analysis.

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Table S1 Age (years), weight (kg) and sex of sheep fed pasture in the Additional dataset.