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Analysis of uncertainties in the estimates of nitrous oxide and methane emissions in the UK's greenhouse gas inventory for agriculture

Alice E. Milne[a*], Margaret J. Glendining[a], Pat Bellamy[b], Tom Misselbrook[c], Sarah Gilhespy[c], Monica Rivas Casado[b], Adele Hulin[d], Marcel van Oijen[e], Andrew P Whitmore[a]

[a]*Rothamsted Research, West Common, Harpenden, Hertfordshire AL5 2JQ*

[b]*Cranfield University, Cranfield, Bedfordshire MK43 0AL*

[c]*Rothamsted Research, North Wyke, Okehampton, Devon EX20 2SB*

[d]*ADAS UK LTD, Pendeford House, Pendeford Business Park, Wobaston Road, Wolverhampton, WV9 5AP*

[e]*Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB*

HIGHLIGHTS

- We calculated the uncertainty in the estimated emissions of N_2O and CH_4 from UK agriculture.
- IPCC Emission factors EF_1 and EF_5 contributed most to the uncertainty in N_2O emissions.
- Enteric fermentation emission factors contributed most to the uncertainty in CH_4 emissions.
- We note the importance of incorporating variables into calculations at the correct scale.

ABSTRACT

The UK's greenhouse gas inventory for agriculture uses a model based on the IPCC Tier 1 and Tier 2 methods to estimate the emissions of methane and nitrous oxide from agriculture. The inventory calculations are disaggregated at country level (England, Wales, Scotland and Northern Ireland). Before now, no detailed assessment of the uncertainties in the estimates of emissions had been done. We used Monte Carlo simulation to do such an analysis. We collated information on the uncertainties of each of the model inputs. The uncertainties propagate through the model and result in uncertainties in the estimated emissions. Using a sensitivity analysis, we found that in England and Scotland the uncertainty in the emission factor for emissions from N inputs (EF_1) affected uncertainty the most, but that in Wales and Northern Ireland, the emission factor for N leaching and runoff (EF_5) had greater influence. We showed that if the uncertainty in any one of these emission factors is reduced by 50%, the uncertainty in emissions of nitrous oxide reduces by 10%. The uncertainty in the estimate for the emissions of methane emission factors for enteric fermentation in cows and sheep most affected the uncertainty in methane emissions. When inventories are disaggregated (as that for the UK is) correlation between separate instances of each emission factor will affect the uncertainty in emissions. As more countries move towards inventory models with disaggregation, it is important that the IPCC give firm guidance on this topic.

1. Introduction

It is widely accepted that anthropogenic actions are affecting the global climate system in a negative way, and that greenhouse gas concentrations in the atmosphere should be stabilized to levels that will prevent negative impacts on the climate system (UNFCCC, 1992). The first quantitative targets for the reduction of greenhouse gas emissions produced by industrialized countries (known as Annex I countries) were made in the Kyoto protocol. In order to monitor progress on this, all Annex I countries are required to report annual emissions and sinks of greenhouse gases from various sectors. To ensure that the calculation of emissions from each sector and reporting is done to a consistent standard a series of guidelines have been produced by the IPCC (IPCC, 1996; Penman et al., 2000; Eggleston et al., 2006). These guidelines set out the methods that should be used to calculate emissions. There are three 'Tiers' of complexity in the calculations. Tier 1 calculations use a basic model, whereby readily-available national or international statistics (known as activity data) are combined with IPCC default emission factors to estimate emissions. The Tier 2 calculations generally disaggregate the activity data and use various emission factors that reflect regional and temporal differences. Tier 3 methods use more complex models and highly disaggregated activity data sources.

Within the model framework the parameters (which include emission factors) and variables (the activity data) may be regarded as inputs to the model. Similarly the calculated emissions may be regarded as the model outputs.

Estimates of emissions are uncertain. This is for a number of reasons. Firstly, the model inputs are themselves uncertain. Activity data are typically estimated from sample surveys and these estimates will be uncertain unless the whole population is surveyed accurately. The model parameters are estimated from experiments and there are errors associated with these derivations. Uncertainties in estimated emissions are also attributed to errors in the conceptualization of the model framework, for example a model may over simplify a process by omitting certain factors.

These errors are less straightforward to quantify and are not included in the quantification of the uncertainty in estimates of emissions (see Eggleston, 2006). All Annex I countries are obliged, as far as possible, to quantify the uncertainties in their estimates of emissions by determining how uncertainties in the model inputs propagate through the model. This is important because it enables the analyst to assess how reliable estimates are and to evaluate statistically whether reductions in emissions are significant.

We are concerned with emissions of nitrous oxide (N_2O) and methane (CH_4) from the agricultural sector. In the UK, this sector contributes substantially to the total emissions of CH_4 and N_2O. Baggot et al. (2007) estimated that, in the UK, approximately 60% of N_2O emissions and 40% of CH_4 emissions were due to agriculture. Brown et al. (2012) compiled the greenhouse gas inventory from agriculture for 1990 to 2010 using the IPCC guidelines published in 2000 (Penman et al., 2000). They did not do a detailed assessment of the uncertainty. We set out to quantify the uncertainty in the emissions of N_2O and CH_4 from agricultural in the UK for the year 2010 and the baseline year (1990), and the uncertainty in the trend between these two years. We considered each of the four countries that make up the UK (England, Wales, Scotland and Northern Ireland) separately. There are several methods that can be used to quantify how the uncertainties in the model inputs propagate through to the model output, i.e. the emissions (see Heuvelink, 1998). We chose to use Monte Carlo simulation because it is straightforward to use, can account for dependencies between inputs, and is arguably more flexible than other methods. This method has been used by other groups estimating emissions from agriculture (Monni et al., 2007; Karimi-Zindashty et al., 2012) and is recommended by the IPCC for inventories that contain large uncertainties (Eggleston et al., 2006). In Monte Carlo simulation model inputs are treated as random variables and are described by a probability density function (PDF). The mean of the PDF describes the expected value of the input and the variance reflects the uncertainty. A value for each input is pseudo-randomly sampled from the PDFs and the model is run to produce an output value. This process is repeated many times (typically thousands of times) resulting in a set of output values which form an empirical distribution that describes the uncertainty. Statistics such as the mean, variance and 95% confidence intervals can be derived from this distribution.

There may be correlations in the errors of two or more inputs. For activity data, these correlations may occur if two or more variables are estimated from the same data source. If variables are estimated using independent sources of data then there will be no correlation in the errors. Similarly, two or more emission factors obtained from the same sets of experiments may have correlated errors. The measure of correlation is typically estimated as part of the statistical procedure used to estimate these parameters (see Milne et al., 2011a). These correlations are accounted for by describing the inputs with multivariate distributions.

As well as quantifying the uncertainty in the emissions (as stated above), our objective was to identify the model inputs that contributed most to the uncertainty of the estimated emissions so that we could target these for improvement in future inventories. To improve both the precision in the estimates of emissions and to reduce the uncertainty in the estimates of emissions, more Tier 2 and Tier 3 calculations are needed in the inventory. These calculations require activity data at a scale of resolution finer than countrywide (for example, statistics on crop areas for the various soil-climatic regions), and new emission factors that match these scales of resolution. These inputs can be time consuming and expensive to derive, and that is why we wanted to identify the inputs that had the most effect on the uncertainty in the total emissions. We undertook a sensitivity analysis to do this. Once we had identified the inputs that influenced uncertainty the most, we explored the effect of reducing their uncertainty by reducing the standard deviation of the PDFs that we used to describe them by 50% in turn.

2. Method

The current greenhouse gas inventory for agriculture in the UK uses the methods from the IPCC guidelines published in 2000 (Penman et al., 2000; Brown et al., 2012). The calculations of CH_4

from enteric fermentation in dairy and beef cows, and the calculations of CH_4 from manure management use Tier 2 methods. All other calculations used Tier 1 methods. Almost all of the activity data and emission factors have some uncertainty associated with them. We used Monte Carlo simulation to quantify how the uncertainties in the model inputs propagate through the model. We used @Risk software (Palisade, 2010) to run our Monte Carlo simulation. Some initial testing showed that running the Monte Carlo simulation for 300,000 iterations gave acceptable convergence. We assessed the convergence of the simulation by considering the stability of the 95% percentile. We chose a convergence tolerance of 1% on the 95% percentile.

In order to do our Monte Carlo simulation, we sought PDFs to describe the uncertainties in the model inputs. This is detailed below.

2.1. Uncertainty in the activity data

2.1.1. Synthetic fertilizer use

To estimate the amount of fertilizer applied to each crop in each country, the fertilizer rates for each crop were multiplied by the respective crop areas. The expected values and standard errors for these variables were calculated using national survey data (Defra, 2010a; Defra, 2010b; DARDNI, 2010). Where the standard errors were small compared to the mean (less than 25%) we assumed the uncertainty was normally distributed, otherwise we assumed a lognormal distribution. This is because when standard errors become larger, there is a greater chance of sampling negative values for the variables (which would not make sense).

2.1.2. Nitrogen applied as sewage sludge

This variable was calculated by multiplying the amount of sewage applied to the land (t year^{-1}) by the expected amount of nitrogen in sewage sludge (kg total N t^{-1} dry solids). The amount of sewage applied to the land was estimated from national statistics (Defra project ES0128, Defra, 2009). Uncertainty information was not available for either of these variables and so we followed Monni et al. (2007) and assumed that the uncertainty in the estimate of nitrogen applied as sewage sludge was normally distributed with 95% confidence interval $\pm 30\%$ of the mean. This estimate is reported in Monni et al. (2007) who derived it using expert opinion.

2.1.3. Nitrogen excretion

Expected values for nitrogen excretion were based on UK-specific data (Misselbrook et al., 2011; Cottrill and Smith, 2007) but no estimates of uncertainty were available. Therefore we followed the IPCC guidelines (Penman et al., 2000), and assumed that the uncertainty was normally distributed with a 95% confidence interval of $\pm 50\%$ of the expected value.

2.1.4. Animal waste management systems (AWMS)

The AWMS activity data describes how animal manure is managed. The data are given as percentages that sum to 100%. Variables of this sort are known as compositional variables and are best described using an additive logistic distribution (Aitchison, 1986). To parameterise this distribution one needs the expected value of each variable in the composition, the standard error and the correlations between the variables. We obtained the expected values from the inventory of ammonia emissions from UK agriculture (Misselbrook et al., 2011). Standard errors were not available and so we followed Monni et al. (2007) and assumed that the standard errors were equal to $20/196$ times the expected values (i.e. the distribution had a 95% confidence interval ±20% of the mean), and that there were no correlations.

2.1.5. Other activity data used to calculate nitrous oxide emissions from soil

Nitrogen returned to the soil as crop residues (R_N), the carbon released from the burning of agricultural residues (R_c), and nitrogen from biological fixation (N_F) are all used to estimate N_2O emissions from soil. These activity data are calculated from crop production (t), the residue to crop product mass ratio, the fraction of the crop residue burnt (kg N kg^{-1} crop N), the fraction of nitrogen in crop (kg N kg^{-1} dry mass), fraction of the residue that remains in the field (kg N kg^{-1} dry mass) and percentage dry matter (%). It was straightforward to source estimates for these six variables, but there was little information on uncertainty. Therefore we followed Monni et al. (2007) and assumed that the PDFs used to describe the uncertainties in R_N, R_c and N_F were normally distributed with means equal to the expected values of each variable and with 95% confidence intervals $\pm 30\%$ of the means. They derived these estimates from expert opinion.

2.1.6. Livestock numbers

The expected values and standard errors for the numbers of each type of animal defined in the inventory were calculated using national survey data (Defra, 2010a). Where the standard errors were small compared to the mean (less than 25%) we assumed the PDFs that described the uncertainty in these inputs were normally distributed, otherwise we assumed a lognormal distribution.

2.2. Uncertainty in the emission factors and model parameters

2.2.1. Emission factors for nitrous oxide

In most instances, the PDFs that describe the uncertainties in the emission factors were parameterised using information in the IPCC guidelines. Brown at al. (2012) used the expected values for emission factors from the guidelines published in 2000 (Penman et al., 2000). Since that time the uncertainty estimates have been revised for some parameters (typically they have increased), and adjustments to some expected values have also been made. We wanted to estimate the uncertainty in Brown et al.'s inventory, and at the same time provide estimates for the uncertainty that could be compared with future versions of the inventory to assess the effect of improvements on the uncertainty estimates. Future versions of the inventory will use the most recent guidelines, and will include more Tier 2 and 3 methods. We used the most recent estimates for confidence intervals (Eggleston et al., 2006), so that the effect of using more Tier 2 and 3 methods is not obscured by the changes in the IPCCs uncertainty information.

Where the range of uncertainty was skewed around the mean we assumed a lognormal distribution. In cases where the range of uncertainty was symmetric we assumed normal distributions. Some of the parameters described proportions (for example the fraction of N input to soils lost as leaching and runoff) and so took values between zero and one. Where the uncertainty was small with respect to the mean we assumed that these inputs were normally distributed, otherwise we used a Beta distribution. The information on uncertainty that we used to parameterise all of these distributions was in the form of an expected value with either a standard deviation or 95% confidence interval. To estimate the parameters of the PDF we used standard formulae that relate the PDF parameter values to the summary statistics, ensuring that our expected values were accurately represented and 95% confidence intervals were as close to those quoted in the literature as possible. Tables 1 and 2 summarise the model parameters for N_2O emissions, the distributions we chose to use, and the source of the PDF parameters (see also supplementary information).

2.2.2. Emission factors for methane from manure management

Tier 2 calculations were used to estimate the emission factors for all of the animal categories except for deer, for which we used the IPCC default values (see Penman et al., 2000). Dietary information for dairy and beef cattle in the UK and UK-specific estimates of animal waste management (see section 2.1.4) were used in the Tier 2 calculations, but apart from that the calculations used parameter values from the IPCC guidelines (IPCC, 1996; Penman et al. 2000). We described the uncertainty in the calculated emission factors using a normal distribution, with a 95% confidence interval of $\pm 20\ \%$ of the expected value for Tier 2 emission factors and with a 95% confidence interval of $\pm 30\ \%$ of the mean for Tier 1 (Eggleston et al., 2006).

2.2.3. Emission factors for methane from enteric fermentation

Tier 2 models were used to estimate the emission factors for dairy and beef cows (see Penman et al., 2000). We estimated the uncertainty in these emission factors by calculating how the uncertainty in the variables used to calculate them propagated through the model. We assumed that all of these variables were normally distributed. Each is listed in Table 3 along with the source of the parameters for the respective PDFs (see also supplementary information).

For all other animal categories we used the IPCC Tier 1 emission factors (Penman et al, 2000). We chose to use the maximum uncertainty range suggested by Eggleston et al. (2006). That is, $\pm 50\%$ of the expected value. Because the confidence interval is large we used a lognormal distribution to describe the uncertainty.

2.3. Uncertainty in the trend over time

The IPCC (Eggleston et al., 2006) defines the trend in emissions (T_t) as $T_t = \frac{e_t - e_0}{e_0}$, where e_0 is emissions in the base year and e_t emissions in the year of interest. We estimated the trend and its associated uncertainty using Monte Carlo simulation.

2.4. Sensitivity analysis

We used ranked correlation analysis (Kendall and Stuart, 1973) to assess the sensitivity of the total emissions to the uncertainty in the model inputs. Spearman's ranked correlation coefficient was estimated between simulated realisations of each model input and the total emissions. The inputs associated with the largest correlations are assumed to influence the overall uncertainty in emissions most.

We identified the two inputs that most influenced the uncertainty in the emissions of N_2O and the two inputs that most influenced the uncertainty in the emissions of CH_4. We explored the effect of reducing the uncertainty in these inputs by halving the standard deviation of the PDFs that describe them.

2.5. Model framework

The emissions from each of the countries were calculated using the same emission factors, but country-specific activity data. In any one iteration of the Monte Carlo simulation the same value for the emission factors was used in the calculations, i.e. we did not resample for each country. This is important otherwise the uncertainty in the estimated emissions from the UK would be artificially reduced (Karimi-Zindashty et al., 2012). Similarly in the calculation of the trend the same emission factors are used in both the base year and the year of interest, and so for any one iteration of the calculation we must use the same values for the emission factors in the two years.

3. Results

3.1. Activity data

Figure 1 shows the expected values for crop areas, managed-grassland areas and the numbers of cattle, sheep, pigs and poultry in each country in 1990 and 2010. It illustrates the broad differences in farming across the UK, and changes over time.

3.2. Nitrous oxide emissions

Tables 4 and 5 show a summary of the estimated emissions of N_2O for England, Wales, Scotland and Northern Ireland, with the uncertainty expressed as a 95% confidence interval. Table 6 shows a summary for the whole of the UK. The results are presented in terms of carbon dioxide equivalents (CO_2-eq). We have used assumed greenhouse gas multipliers of 310 for N_2O and 21 for CH_4 (IPCC, 1997). Of the four countries, England produced by far the most N_2O emissions. In 1990 the estimated emissions for England were 23.3 Tg N_2O year^{-1} CO_2-eq, compared with 5.13 in Scotland, 2.83 in Northern Ireland and 3.54 in Wales. In all countries approximately 60% of the calculated N_2O emissions were direct emissions from soil and approximately 35% were indirect emissions from soil. This similarity is largely driven by the model we used to calculate emissions. The emissions from manure management are comparatively small in all countries. Proportionally they are largest in Northern Ireland (8%) and smallest in England (5%). This reflects the differences in the proportions of arable farming and livestock farming in each country: England has the largest proportion of arable farming whereas Northern Ireland's farming is more livestock based with proportionally larger numbers of pigs and cows (Fig. 1). For each country, there is a reduction in the estimated emissions of N_2O between 1990 and 2010 (Table 7). According to the 95% confidence intervals, this trend was significantly different from zero for the UK and, when considered separately, for England, Wales and Scotland.

For each subcategory in Tables 4 and 5, the 95% confidence intervals, as percentages of the expected values, were similar across the countries and years. This is because the uncertainties are primarily caused by the uncertainties in the emission factors (which are the same for all countries and years) and have little to do with the uncertainties in the activity data. Another consequence of this is that, in absolute terms, the 95% confidence intervals for the total emissions are smaller in 2010 compared with 1990, when the estimated emissions were larger for each country. The largest uncertainty is for the estimate of indirect emissions, due to the large uncertainties in the estimates of the emission factors used in the calculations (EF_4, EF_5, and $Frac_{LEACH}$).

Figure 2 shows the empirical distribution of the estimate of total N_2O emissions from soils in the UK in 1990 and 2010. The distribution is skewed because the emission factors for N_2O emissions are skewed. The distribution for 2010 is less spread illustrating the reduction in the uncertainty.

3.2. Methane emissions

Tables 8–10 summarise of the estimated emissions, with 95% confidence interval, of CH_4 for England, Wales, Scotland, Northern Ireland and the UK. The estimated proportions of emissions from animal manures and enteric fermentation for each animal source are illustrated in Fig. 3. Cattle, pigs and sheep contribute most to emissions and so we have detailed the emissions from these sources in Tables 8 and 9.

Of the four countries, English agriculture produces the most CH_4 emissions as a result of the larger numbers of animals. Between 1990 and 2010 the estimated emissions from cattle manures decreased in England, but increased slightly in the other countries despite the reduction in the numbers of cattle. This is because the calculated emission factors for cattle were larger for 2010 than 1990. This was a consequence of changes in the way animal manure is managed and increases in the gross energy intake of cows, associated with increasing body weight and higher milk production. Changes in the way pig and poultry manure was managed between 1990 and 2010 also result in changes in emission factors between the two years.

The reduction in animal numbers was sufficient to reduce estimated emissions from enteric fermentation in cattle in England, Scotland and Wales, although in Northern Ireland estimated emissions increased. This is because the calculated emission factors for cattle were larger in 2010 compared with 1990, because of increasing body weight and greaater milk production and hence intake. The estimated total CH_4 emissions from England and Scotland significantly reduced between 1990 and 2010 (see Table 11). In Wales the reduction was not significantly different from zero. Emissions from Northern Ireland changed little (see Table 9). Figure 4 shows the empirical distributions of the estimates of total CH_4 emissions in the UK. The distribution for 2010 is less spread illustrating the reduction in the uncertainty.

3.3. Sensitivity analysis

According to the Spearman rank correlation coefficients, the five inputs that most affect the uncertainty in N_2O emissions in 1990 and 2010 are: the emission factor for emissions from the direct application of nitrogen fertilizer (EF_1); the emission factor for nitrogen leaching and runoff (EF_5); the fraction of nitrogen lost to leaching ($Frac_{LEACH}$); the emission factor for animal waste management for pasture, range of paddock (EF_3) and the emission factor for nitrogen deposition (EF_4). The rank correlation coefficients for 2010 are shown in Fig. 5 (the results for 1990 were similar). The emission factor EF_1 has the largest impact on the uncertainty of N_2O emissions in England and Scotland. In Wales and Northern Ireland EF_5 is marginally more important. The difference is because there are relatively fewer direct emissions from crop residues in these two countries because a greater proportion of land is in grass rather compared with England and Scotland. The next most influential inputs were on nitrogen excretion of cows and sheep (data not shown).

Reducing the uncertainty in EF_1 by halving the standard deviation in its associated PDF resulted in the standard deviation of the modelled emissions reducing by of 10% in both 1990 and 2010. The same reduction in EF_5 (i.e. 50%) also resulted in a 10% reduction in the standard deviation of the modelled emissions of N_2O from the UK in both 1990 and 2010.

The inputs that most affected the uncertainty in CH_4 emissions were similar across the countries, although the order of importance varied slightly from country to country (Fig. 6). According to the Spearman rank correlation coefficient, in Wales and Scotland the emission factor for enteric fermentation from adult sheep had the largest impact on uncertainty, whereas in England and Northern Ireland model inputs on cattle emissions were more important. The most important inputs are: the emission factors for enteric fermentation for dairy replacements, adult sheep, beef (other > 1year) and beef calves; the maintenance parameter for lactating cattle (Cfi); and feed digestibility for both beef and dairy cows. The last three model inputs are used to calculate the enteric fermentation emission factors for beef and dairy cows. According to the Spearman rank correlation coefficient the uncertainties in the emission factors for animal waste and the uncertainty in the numbers of animals have much less effect on the uncertainty in emissions.

Reducing the uncertainty in the emission factor for enteric fermentation in dairy replacements in England by halving the standard deviation in its associated PDF resulted in a reduction in the standard deviation of modelled CH_4 from England of 10% in 1990 and 14% in 2010. The same reduction in the uncertainty for the emission factor for enteric fermentation in adult sheep in England (i.e. 50%) resulted in a 7% reduction in the standard deviation of the modelled emissions CH_4 from England in both 1990 and 2010.

4. Discussion

In all countries there was a decrease in N_2O emissions from agriculture between 1990 and 2010, and the uncertainty in the estimated emissions reduced proportionally. The reduction in emissions was significantly different from zero for all countries except Northern Ireland. In all countries, the reduction in emissions from synthetic fertilizer is primarily a consequence of the reduction in fertilizer applied to grasslands. The reduction in emissions from animal manures primarily resulted from the reduction in the numbers of cattle, sheep and pigs.

Uncertainty in the emissions of N_2O were primarily driven by the uncertainties in the emission factors. The uncertainty in the activity data is small compared to these inputs and has much less impact. Of the emission factors, EF_1, EF_5 and $Frac_{LEACH}$ have most impact. To reduce uncertainty, effort needs to be made to improve these estimates.

Nitrous oxide emissions are known to have large variation both in time and space (e.g. Stehfest and Bouwman, 2006). To account for temporal variation, the IPCC recommended that emission factors should only be estimated from data collected from a period of at least a year (Penman et al., 2000). Variation in space will substantially contribute to the large confidence intervals given for the IPCC emission factors. Spatial variations are largely driven by soil properties, and the influence of soil properties changes with scale (see Milne et al., 2011b). Milne et al. showed that at the landscape scale, changes in the parent material have a significant impact on emission rates, and that at this scale nitrate concentration is strongly correlated with N_2O emissions (which supports the assumptions in the Tier 1 model that we used to estimate emissions). It follows that to improve emission estimates, emission factors need to be derived for more specific soil-climate systems.

There is a substantial difference between the 95% confidence interval for the estimate of total N_2O emissions from soils in 2010 given here compared with that given by Brown et al. (2012). Their confidence interval, which is based on expert opinion, was (-93%, +253%) whereas ours is (-56%, +143%). The uncertainty on our estimate for N_2O from soils is much larger than that derived by Monni et al. (2007), however, who quote a 95% confidence interval of (—52%, +70%). This is because Monni used the more conservative estimates for the uncertainty in EF_1 from IPCC (1997), whereas we derived ours using the more recent IPCC guidelines (Eggleston et al., 2006).

The estimated total CH_4 emissions from England and Scotland significantly reduced between 1990 and 2010. In Wales there was a reduction but this was not significantly different from zero. Emissions from Northern Ireland remain little changed. Reductions in emissions were primarily a consequence of the reductions in the numbers of cows, pigs and sheep.

The uncertainty in the emission estimate for CH_4 is small (a confidence interval of less than ±22%) compared with that for N_2O emissions, which are an order of magnitude larger. The largest uncertainties are associated with emissions from cattle. This is because the uncertainty in the emission factors for cattle are large. The model inputs that contribute most to the uncertainty in CH_4 emissions are the emission factors for enteric fermentation in cattle and sheep. In the inventory reported on here we used Tier 2 calculations to estimate the emissions factors for beef and dairy cows. The Tier 2 calculations derive the emissions factors from model inputs such as the maintenance parameter (Cfi) and feed digestibility. The uncertainties in these inputs were taken from Monni et al. (2007) and are based on expert opinion. Their importance in the uncertainty calculations of the inventory highlights the need for better estimates of their uncertainty.

Reduction in the uncertainty of CH_4 emissions could be achieved with better information on the emission factors for enteric fermentation in cattle and sheep. Disaggregating cattle and sheep, based on breed or how they are managed should lead to emission factors with improved precision and smaller uncertainty. This is likely to lead to increases in the uncertainties in the activity data, however, and so we must be cautious in our approach. This argument also applies when we disaggregate the activity data used to estimate N_2O emissions, but because the uncertainties in the emission factors for CH_4 are smaller than those for N_2O emissions, it is more of an issue for CH_4 estimates.

Disaggregation of the inventory will lead to a more complex framework, and those compiling inventories shall need to ensure that emission factors and parameters are applied at the correct scale. That is to say, if an emission factor is used in more than one calculation, then the same sampled value must be used in any one iteration of the Monte Carlos simulation (see Karimi-Zindashty et al., 2012).

Brown et al. (2012) reported uncertainty estimates for various animal sources of CH_4 emissions in the UK. Their 95% confidence intervals for emissions from manure management of cattle, sheep, pigs and poultry are larger than ours, whereas their 95% confidence intervals for emissions from enteric fermentation in cattle, sheep, pigs are somewhat smaller. The 95% confidence intervals in Brown et al. (2012) were calculated using assumptions based on Williams (1993). Our percentage uncertainty in CH_4 emissions from both enteric fermentation and manure management were smaller than those reported in Monni et al. (2007). In our analysis the uncertainties in emissions from enteric fermentation and manure management were approximately $\pm 20\%$ and $\pm 12\%$ (for each country) respectively compared with $\pm 25\%$ and $\pm 20\%$ in Monni et al. (2007) (all expressed in terms of 95% confidence intervals as a percentage of the mean). This is a result of the larger uncertainties associated with their emission factors for CH_4 from cattle. Karimi-Zindashty et al. (2012) reported a similar percentage uncertainty for CH_4 emissions from enteric fermentation to ours. Their percentage emissions from manure management were much larger however (approximately -34% to 39%). This relates to differences in the uncertainties of the emission factors. We used the IPCC default uncertainty estimates, whereas Karimi-Zindashty et al. calculated theirs by error propagation.

5. Conclusion

Between 1990 and 2010, N_2O emissions from agriculture in the UK reduced from 34.7 Tg CO_2-eq year^{-1}, with 95% confidence interval (15.14, 84.32) to 28.1 Tg CO_2-eq year^{-1}, with 95% confidence interval (12.3, 67.3). Similarly emissions of CH_4 reduced from 22.34 Tg N_2O year^{-1} CO_2-eq, with 95% confidence interval (20.04, 24.90) to 17.80 Tg N_2O year^{-1} CO_2-eq, with 95% confidence interval (16.13, 19.65). Both reductions were significantly different from zero. The reductions were in part driven by the contraction of the agricultural sector.

The current inventory structure does not allow for the effects of mitigation strategies such as the precision application of nitrogen, denitrification inhibitors or manipulating diet, which should also impact emissions. To improve the precision of estimates in the UK greenhouse gas inventory for agriculture there is a recognised need to move towards Tier 2 and Tier 3 methods with the inclusion of mitigation effects. In doing this we shall use emission factors that are derived for UK conditions and we are likely to disaggregate the activity data for use at finer scales than country level. Improved emission factor estimates will almost certainly have smaller uncertainty, but conversely, further disaggregation of the activity data might result in increased uncertainty. Our approach must be balanced.

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Table 1

The PDFs used to represent the uncertainty in the emission factors used to calculate N_2O emissions. The sources of the parameters for the PDFs are listed.

Parameter name	Abbreviation	PDF	Source of parameterization
Emission factor for emissions from N inputs	EF_1	Lognormal	Expected value, IPCC (1996), uncertainty Eggleston et al. (2006).
Emission from histosols	EF_2	Lognormal	Expected value, Penman et al. (2000), uncertainty Eggleston et al. (2006).
Emissions from AWMS	EF_3	Lognormal	Penman et al. (2000).
N deposition factor	EF_4	Lognormal	Expected value, IPCC (1996), uncertainty Eggleston et al. (2006).
N leaching and runoff factor	EF_5	Lognormal	IPCC (1996).

Table 2

The PDFs used to represent the uncertainty in model parameters used to calculate N_2O emissions. The sources of the parameters for the PDFs are listed.

Parameter name	Abbreviation	PDF	Source of parameterization
Grass N fixation rate	-	Lognormal	Mean given by Eunice Lord, ADAS pers comm., uncertainty expert opinion.
Emission ratios for crop residue burning	-	Normal	IPCC (1996).
N:C ratio for wheat	-	Normal	IPCC (1996), Table 4-17.
N:C ratio for oats, barley and linseed	-	Normal	IPCC (1996), Table 4-17.
Fraction of N fertilizer emitted as NOx and NH_3	$Frac_{GASF}$	Beta	Expected value, IPCC (1996), uncertainty Eggleston et al. (2006).
Fraction of N excretion emitted as NOx and NH_3	$Frac_{GASM}$	Beta	Expected value, IPCC (1996), uncertainty Eggleston et al. (2006).
Fraction of N input to soils lost as leaching and runoff	$Frac_{LEACH}$	Beta	IPCC (1996), Table 4-24.

Table 3

The sources of the PDF parameters for model inputs used to calculate the emission factors for enteric fermentation.

Parameter	Abbreviation	Source of parameterization	
		Expected value	Uncertainty
Maintenance	Cf_i	Penman et al. (2000)	Monni et al. (2007)
Feeding activity	C_a	Penman et al. (2000)	Monni et al. (2007)
Net Energy	C	Penman et al. (2000)	Monni et al. (2007).
Pregnancy	$C_{Pregnancy}$	Penman et al. (2000)	Monni et al. (2007)
CH_4 conversion rate	Y_M	Penman et al. (2000)	Penman et al. (2000)
Feed energy density		Penman et al. (2000)	McDonald et al. (1981), based on range for animal feedstuffs.
Digestible energy		B Cottrill, ADAS	Monni et al. (2007)
Milk fat content		UK data (dairy cows) and Irish EPA report (beef cows)	Monni et al. (2007)
Milk yield		UK data (dairy cows) and Irish EPA report (beef cows)	The Farm Business Survey.
Animal weight		Expected values UK slaughter data	Monni et al. (2007)

Table 4

Summary of N_2O emissions / Tg CO_2-eq year^{-1} from agriculture in England and Wales

Source	Emissions in 1990			Emissions in 2010		
	Mean	95% Confidence interval		Mean	95% Confidence interval	
England						
Soils - direct	13.79	5.72	30.89	11.47	4.75	25.75
Soils - indirect	8.09	0.61	39.85	6.27	0.48	30.79
Biological fixation from improved grass	0.10	0.02	0.28	0.09	0.02	0.28
Field burning of agricultural residues	0.07	0.04	0.11	0.00	0.00	0.00
Direct from animal waste management systems	1.25	0.69	2.15	0.94	0.53	1.58
Total emissions in England	**23.30**	**9.64**	**58.45**	**18.78**	**7.78**	**46.57**
Wales						
Soils - direct	2.06	1.00	3.92	1.58	0.79	2.95
Soils - indirect	1.27	0.11	6.01	0.96	0.08	4.48
Biological fixation from improved grass	0.02	0.01	0.07	0.03	0.01	0.08
Field burning of agricultural residues	0.00	0.00	0.00	0.00	0.00	0.00
Direct from animal waste management systems	0.19	0.10	0.33	0.14	0.07	0.26
Total emissions in Wales	**3.54**	**1.61**	**8.52**	**2.71**	**1.26**	**6.21**

Table 5

Summary of N_2O emissions / Tg CO_2-eq year^{-1} from agriculture in the Scotland and Northern Ireland

Source	Emissions in 1990			Emissions in 2010		
	Mean	95% Confidence interval		Mean	95% Confidence interval	
Scotland						
Soils - direct	3.02	1.40	6.11	2.47	1.15	5.00
Soils - indirect	1.78	0.15	8.43	1.40	0.12	6.62
Biological fixation from improved grass	0.03	0.01	0.08	0.03	0.01	0.10
Field burning of agricultural residues	0.01	0.00	0.01	0.00	0.00	0.00
Direct from animal waste management systems	0.30	0.16	0.55	0.23	0.11	0.43
Total emissions in Scotland	**5.13**	**2.30**	**12.29**	**4.14**	**1.86**	**9.79**
Northern Ireland						
Soils - direct	1.57	0.75	3.10	1.40	0.68	2.70
Soils - indirect	1.01	0.09	4.70	0.88	0.08	4.09
Biological fixation from improved grass	0.02	0.00	0.06	0.02	0.00	0.05
Field burning of agricultural residues	0.00	0.00	0.00	0.00	0.00	0.00
Direct from animal waste management systems	0.23	0.12	0.41	0.21	0.11	0.37
Total emissions in Northern Ireland	**2.83**	**1.30**	**6.74**	**2.51**	**1.17**	**5.91**

Table 6

Summary of N_2O emissions / Tg CO_2-eq year^{-1} from agriculture in the UK

Source	Emissions in 1990			Emissions in 2010		
	Mean	95% Confidence interval		Mean	95% Confidence interval	
UK						
Soils - direct	20.41	9.04	43.54	16.91	7.52	36.01
Soils - indirect	12.11	1.00	57.41	9.48	0.80	44.82
Biological fixation from improved grass	0.17	0.04	0.49	0.17	0.04	0.50
Field burning of agricultural residues	0.08	0.05	0.12	0.00	0.00	0.00
Direct from animal waste management systems	1.96	1.09	3.39	1.52	0.86	2.60
Total emissions	**34.73**	**15.14**	**84.32**	**28.09**	**12.30**	**67.30**

Table 7

The trend in emissions of N_2O from 1990 to 2010.

Country	Trend	95% Confidence interval	
England	-0.19	-0.30	-0.08
Wales	-0.23	-0.36	-0.06
Scotland	-0.19	-0.32	-0.04
Northern Ireland	-0.10	-0.27	0.10
UK	-0.20	-0.26	-0.11

Table 8

Summary of CH_4 emissions / Tg CO_2-eq year^{-1} from agriculture in England and Wales

Source	Emissions in 1990			Emissions in 2010		
	Mean	95% Confidence interval		Mean	95% Confidence interval	
England						
Cattle manure	1.16	0.98	1.35	1.08	0.91	1.25
Pig manure	1.25	1.12	1.39	0.42	0.37	0.46
Total emissions from animal manures	*2.61*	*2.37*	*2.84*	*1.67*	*1.49*	*1.84*
Enteric fermentation in cattle	8.33	6.76	10.20	6.71	5.61	8.03
Enteric fermentation in sheep	2.01	1.31	2.99	1.38	0.90	2.06
Total emissions from enteric fermentation	*10.61*	*8.85*	*12.68*	*8.30*	*7.06*	*9.75*
Emissions from field burning	*0.24*	*0.18*	*0.31*	*0.00*	*0.00*	*0.00*
Total emissions	**13.47**	**11.68**	**15.54**	**9.96**	**8.71**	**11.43**
Wales						
Cattle manure	0.20	0.17	0.23	0.21	0.18	0.24
Sheep manure	0.032	0.027	0.037	0.024	0.021	0.028
Pig manure	0.020	0.015	0.027	0.003	0.002	0.004
Total emissions from animal manures	0.26	0.23	0.29	0.25	0.22	0.28
Enteric fermentation in cattle	1.56	1.29	1.88	1.36	1.13	1.62
Enteric fermentation in sheep	1.10	0.71	1.66	0.85	0.55	1.27
Total emissions from enteric fermentation	2.68	2.18	3.31	2.23	1.84	2.72
Emissions from field burning	0.018	0.014	0.023	0.00	0.00	0.00
Total emissions	**2.94**	**2.45**	**3.57**	**2.48**	**2.09**	**2.97**

Table 9

Summary of CH_4 emissions / Tg CO_2-eq year^{-1} from agriculture in Scotland and Northern Ireland

Source	Emissions in 1990			Emissions in 2010		
	Mean	95% Confidence interval		Mean	95% Confidence interval	
Scotland						
Cattle manure	0.20	0.17	0.22	0.21	0.19	0.24
Pig manure	0.09	0.08	0.10	0.05	0.04	0.06
Total emissions from animal manures	0.34	0.31	0.36	0.29	0.26	0.32
Enteric fermentation in cattle	2.14	1.73	2.62	1.93	1.56	2.36
Enteric fermentation in sheep	1.00	0.65	1.50	0.69	0.45	1.03
Total emissions from enteric fermentation	3.17	2.60	3.84	2.64	2.19	3.18
Emissions from field burning	0.018	0.014	0.022	0.00	0.00	0.00
Total emissions	**3.52**	**2.96**	**4.20**	**2.94**	**2.48**	**3.48**
Northern Ireland						
Cattle manure	0.19	0.17	0.22	0.27	0.23	0.31
Pig manure	0.13	0.12	0.15	0.05	0.04	0.05
Total emissions from animal manures	0.35	0.32	0.38	0.35	0.31	0.39
Enteric fermentation in cattle	1.76	1.42	2.15	1.87	1.55	2.25
Enteric fermentation in sheep	0.28	0.18	0.42	0.18	0.12	0.27
Total emissions from enteric fermentation	2.07	1.72	2.48	2.08	1.74	2.46
Emissions from field burning	0.001	0.001	0.001	0.00	0.00	0.00
Total emissions	**2.42**	**2.06**	**2.83**	**2.43**	**2.09**	**2.81**

Table 10

Summary of CH_4 emissions / Tg CO_2-eq year^{-1} from agriculture in the UK.

Source	Emissions in 1990	95% Confidence interval		Emissions in 2010	95% Confidence interval	
Total emissions from animal manures	3.55	3.32	3.79	2.56	2.38	2.74
Total emissions from enteric fermentation	18.52	16.23	21.07	15.25	13.59	17.08
Emissions from field burning	0.27	0.20	0.33	0.00	0.00	0.00
Total emissions	**22.34**	**20.04**	**24.90**	**17.80**	**16.13**	**19.65**

Table 11

The trend in emissions of CH_4 from 1990 to 2010.

Country	Trend	95% Confidence interval	
England	-0.257	-0.382	-0.113
Wales	-0.15	-0.34	0.08
Scotland	-0.160	-0.332	-0.041
Northern Ireland	0.010	-0.168	0.209
UK	-0.19	-0.29	-0.10

Figure Captions:

Fig. 1 The expected values for crop areas, managed grassland areas and the numbers of cattle, sheep, pigs and poultry in England, Wales, Scotland and Northern Ireland in 1990 and 2010.

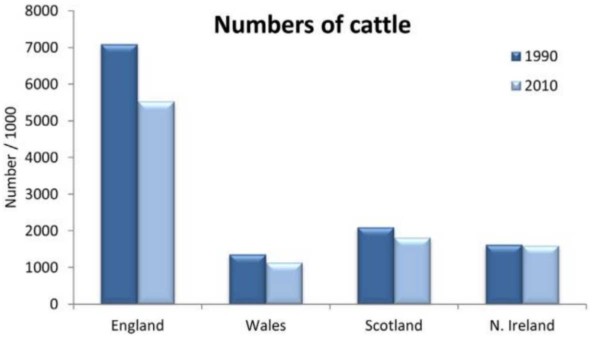
Fig 2. Empirical distributions of the estimated emissions of N_2O in the UK for 1990 and 2010 derived by Monte Carlo simulation.

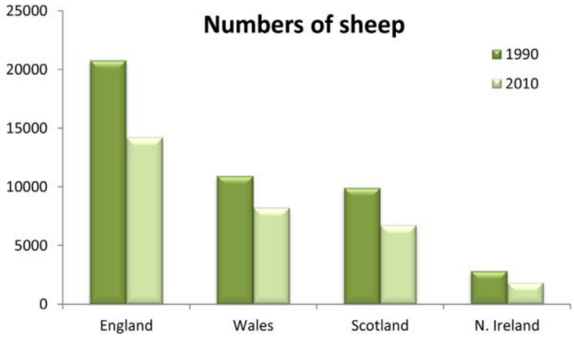
Fig 3. The estimated proportions of CH_4 emissions from enteric fermentation and animal manures for each animal source.

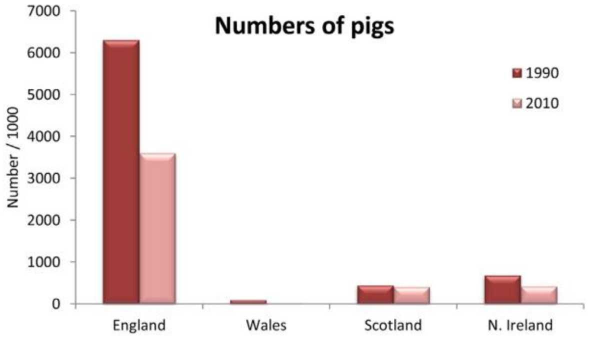
Fig 4. Empirical distributions of the estimated emissions of CH_4 in the UK for 1990 and 2010 derived by Monte Carlo simulation.

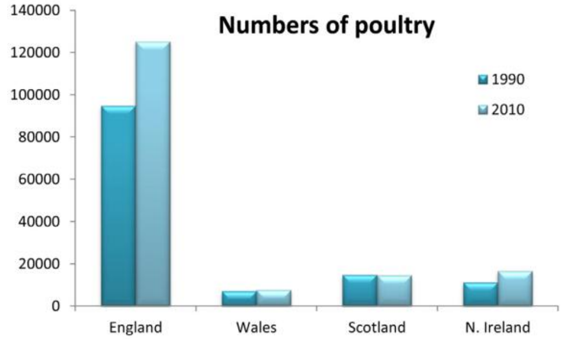
Fig 5. Tornado graphs showing the model inputs that, according to the Spearman Rank correlation coefficient, most affected the uncertainty in estimated emissions of N_2O for each country in 2010.

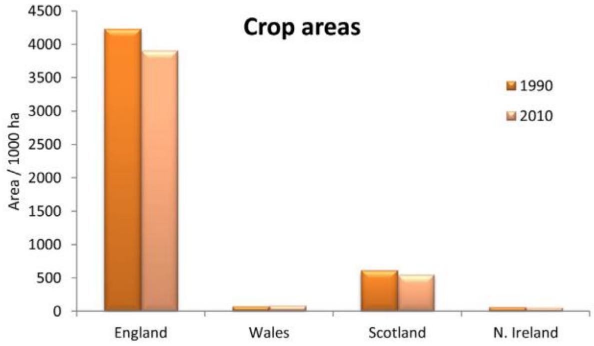
Fig 6. Tornado graphs showing the model inputs that, according to the Spearman Rank correlation coefficient, most affected the uncertainty in estimated emissions of CH_4 for each country in 2010.

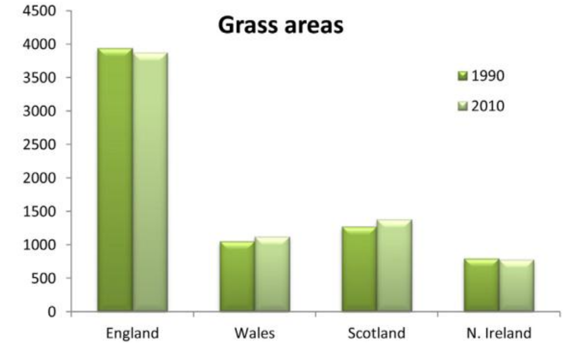

Numbers of cattle
Number / 1000
8000
7000
6000
5000
4000
3000
2000
1000
0
1990
2010
England
Wales
Scotland
N. Ireland

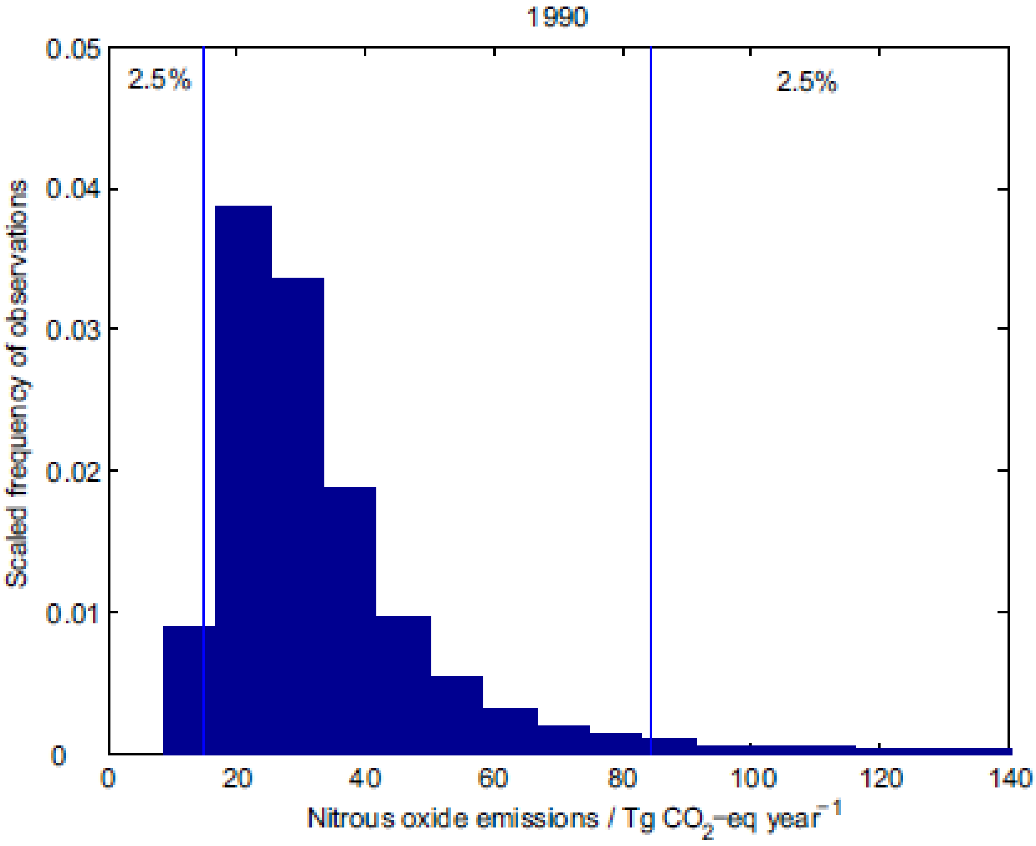

Numbers of sheep
25000
20000
15000
10000
5000
0
1990
2010
England
Wales
Scotland
N. Ireland

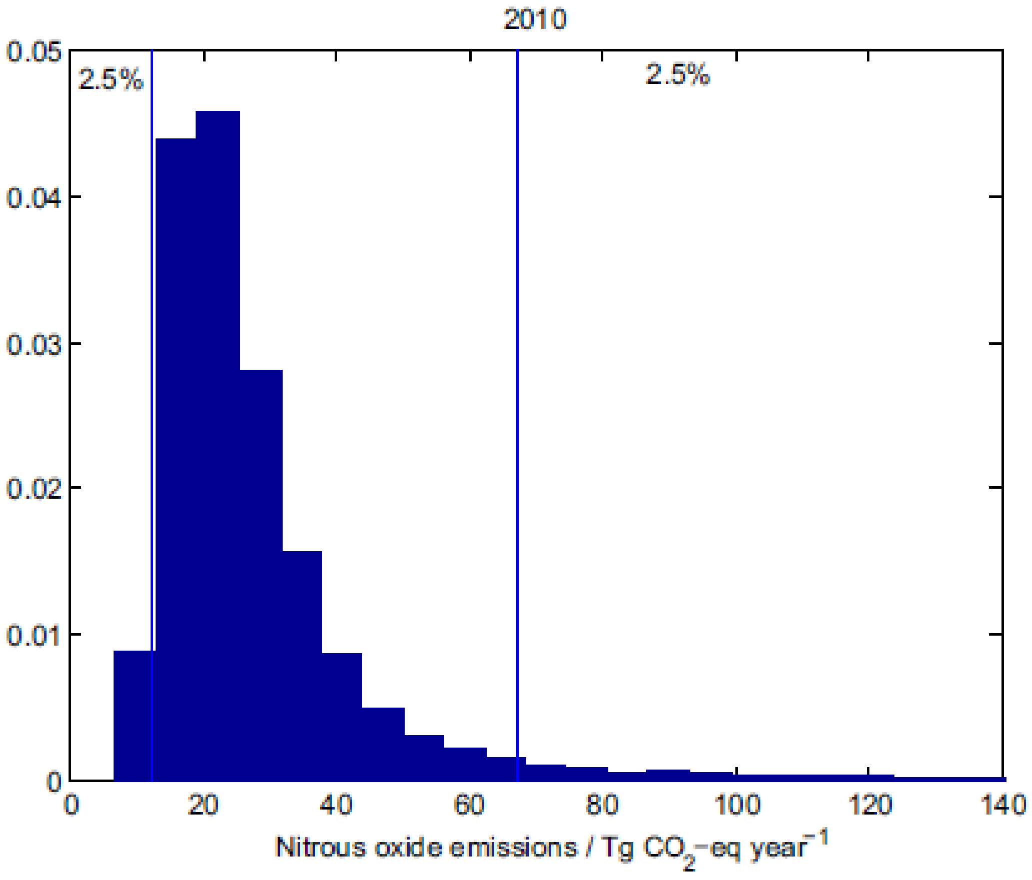

Numbers of pigs
Number / 1000
7000
6000
5000
4000
3000
2000
1000
0
1990
2010
England
Wales
Scotland
N. Ireland

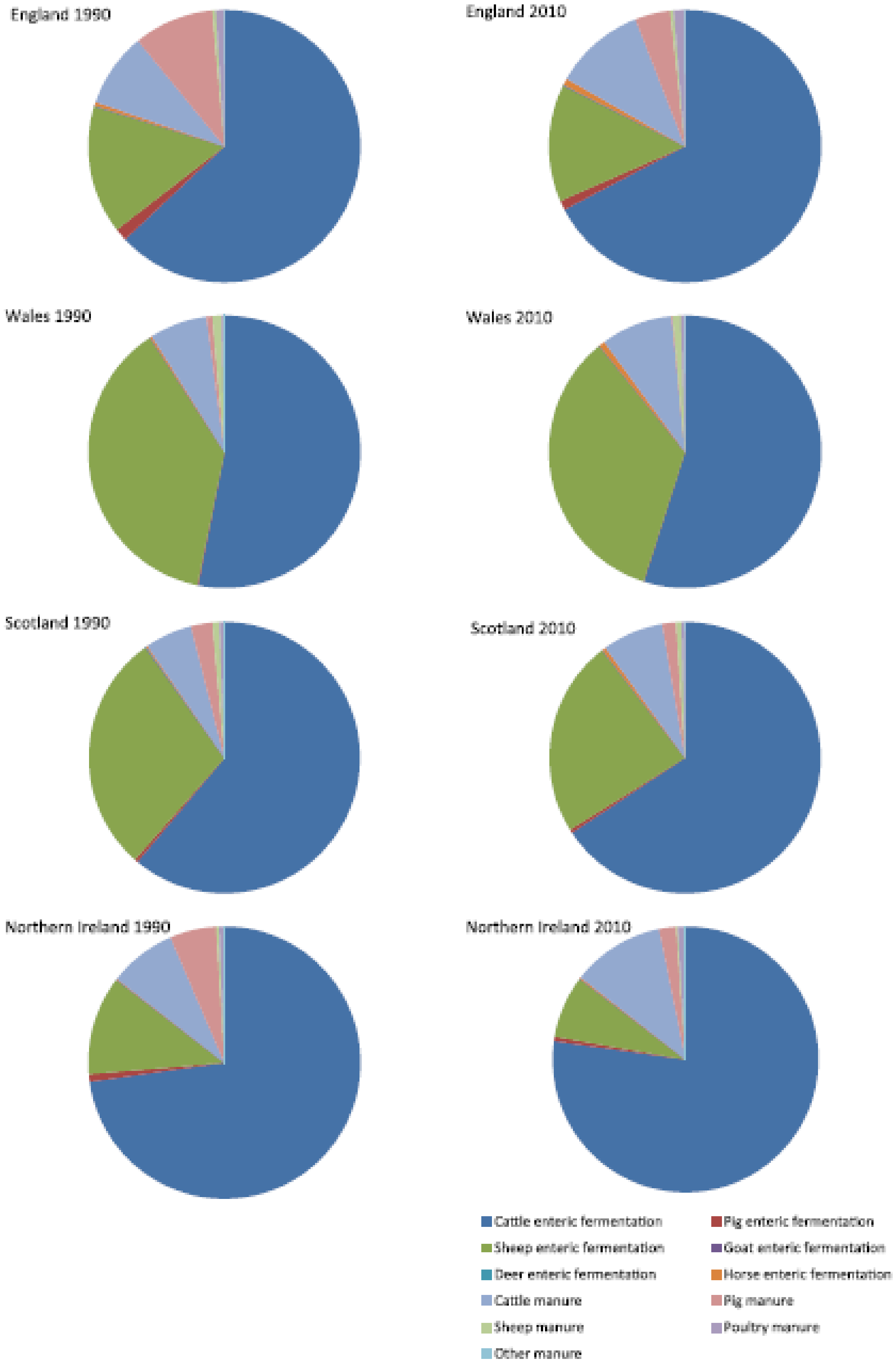

Numbers of poultry
140000
120000
100000
80000
60000
40000
20000
0
1990
2010
England
Wales
Scotland
N. Ireland

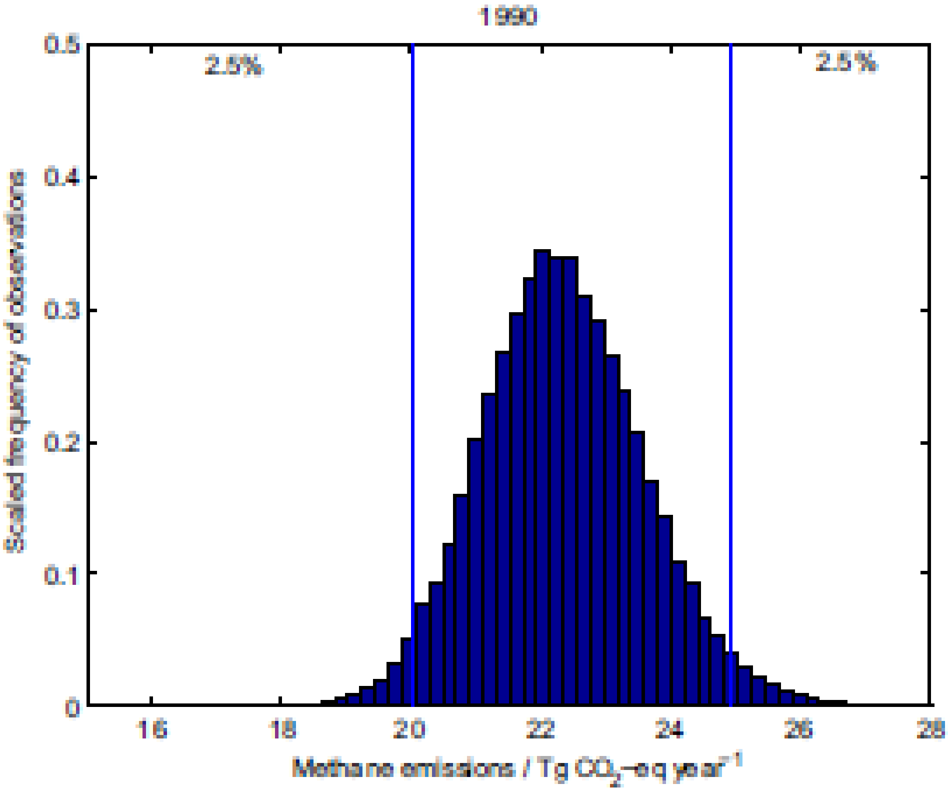

Crop areas
Area / 1000 ha
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1990
2010
England
Wales
Scotland
N. Ireland

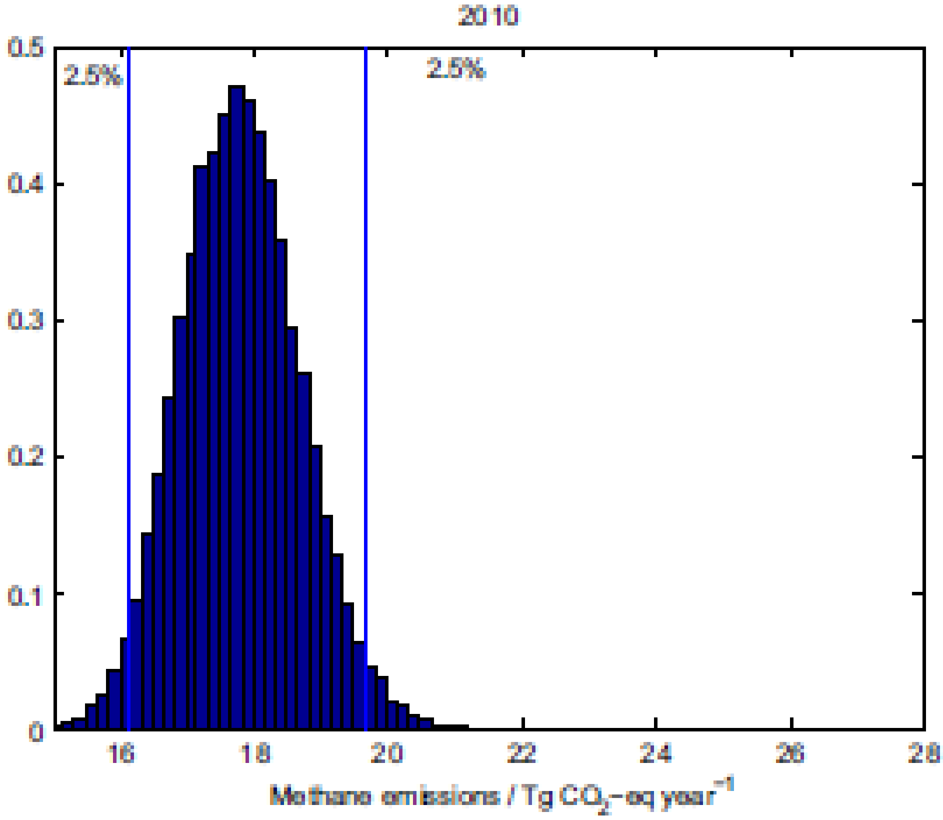

Grass areas
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1990
2010
England
Wales
Scotland
N. Ireland

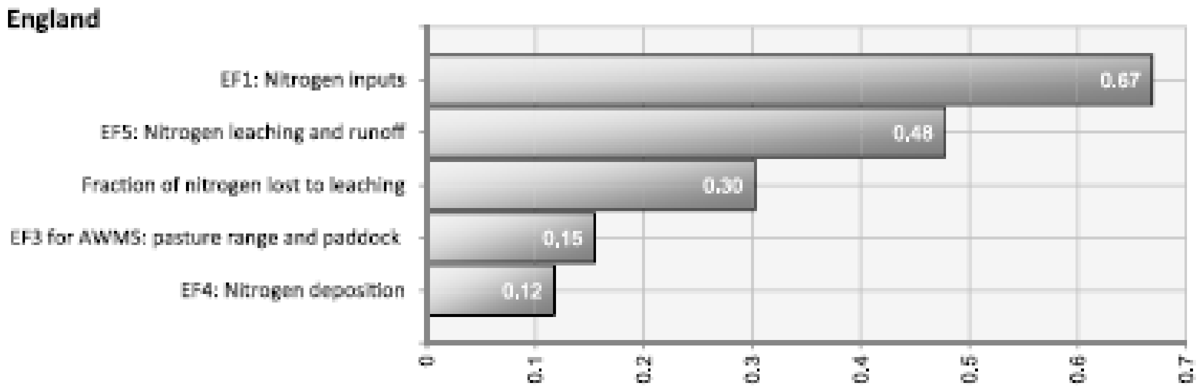

1990
2.5%
2.5%
Scaled frequency of observations
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
120
140
Nitrous oxide emissions / Tg CO_2–eq $year^{-1}$

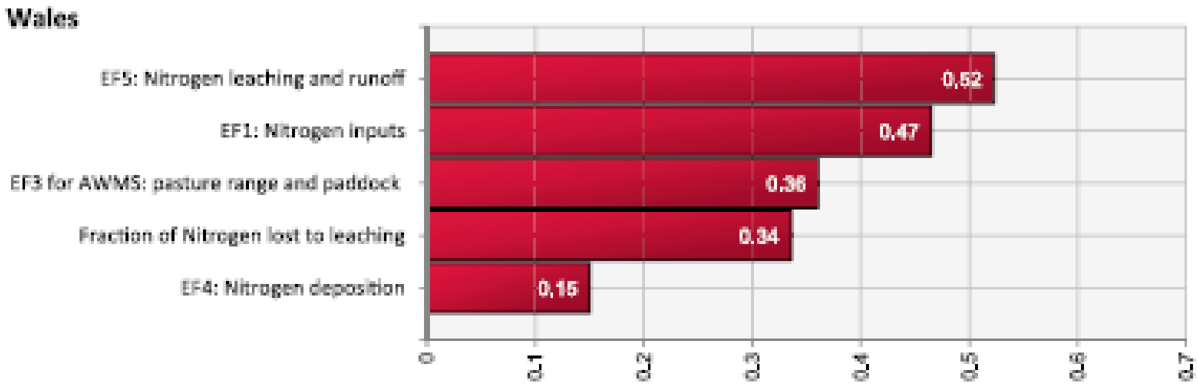

2010
2.5%
2.5%
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
120
140
Nitrous oxide emissions / Tg CO_2–eq $year^{-1}$

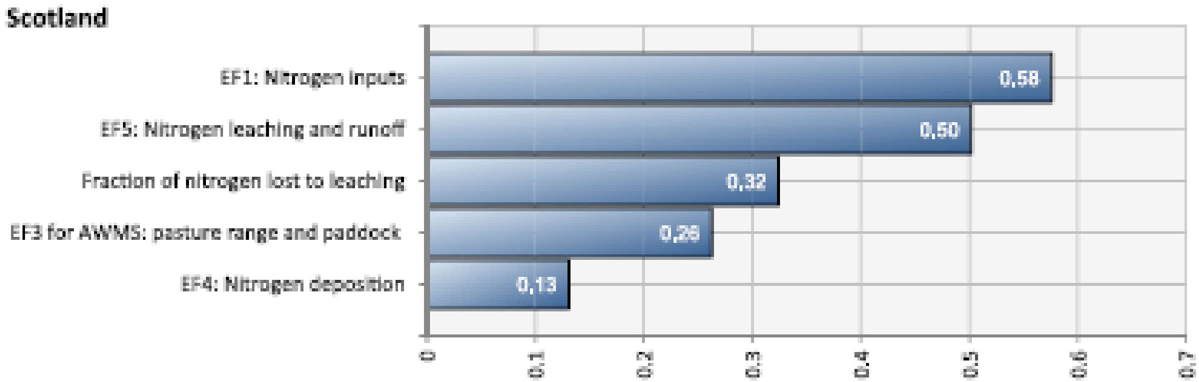

England 1990
England 2010
Wales 1990
Wales 2010
Scotland 1990
Scotland 2010
Northern Ireland 1990
Northern Ireland 2010
Cattle enteric fermentation
Pig enteric fermentation
Sheep enteric fermentation
Goat enteric fermentation
Deer enteric fermentation
Horse enteric fermentation
Cattle manure
Pig manure
Sheep manure
Poultry manure
Other manure

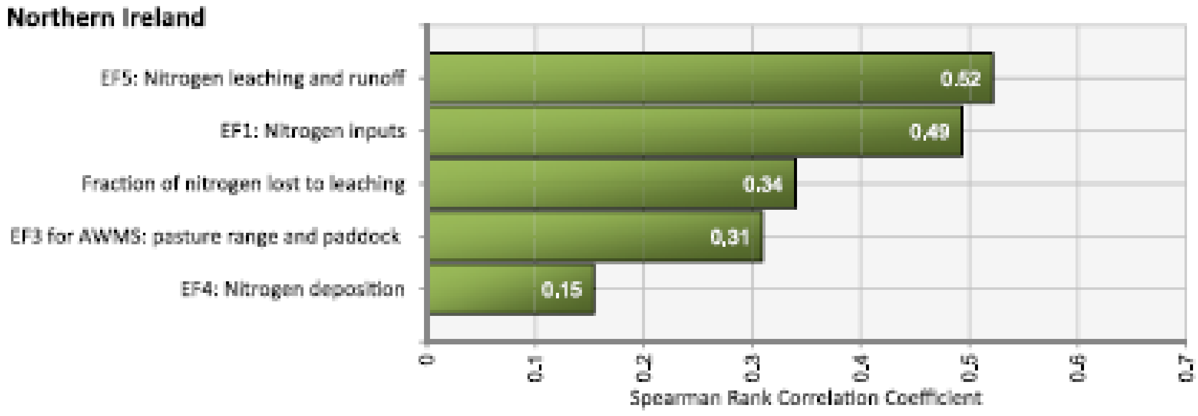

1990
2.5%
2.5 %
Scaled frequency of observations
0
0.1
0.2
0.3
0.4
0.5
16
18
20
22
24
26
28
Methane emissions / Tg CO$_2$−eq year^{-1}

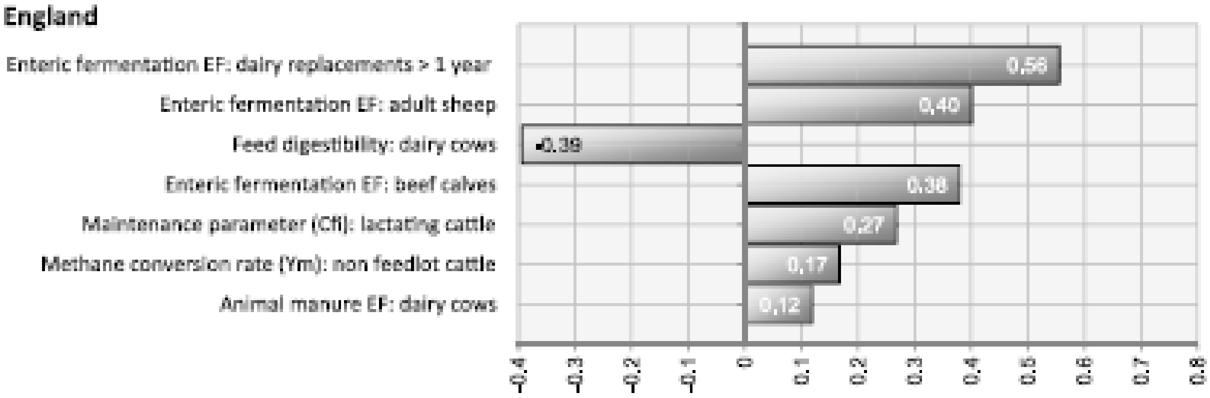

2010
2.5%
2.5%
0
0.1
0.2
0.3
0.4
0.5
16
18
20
22
24
26
28
Methane emissions / Tg CO$_2$−eq year^{-1}


England
EF1: Nitrogen inputs
0.67
EF5: Nitrogen leaching and runoff
0.48
Fraction of nitrogen lost to leaching
0.30
EF3 for AWMS: pasture range and paddock
0.15
EF4: Nitrogen deposition
0.12
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

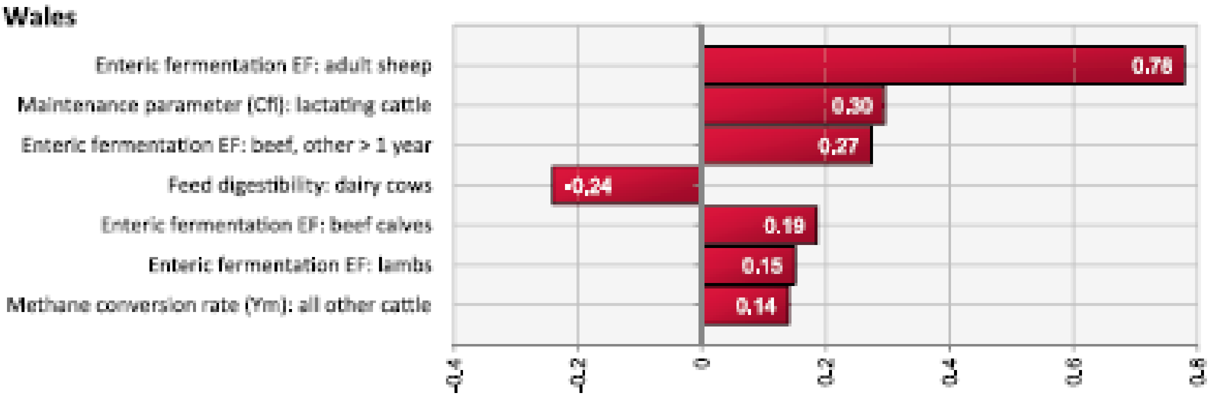

Wales
EF5: Nitrogen leaching and runoff
0.52
EF1: Nitrogen inputs
0.47
EF3 for AWMS: pasture range and paddock
0.36
Fraction of Nitrogen lost to leaching
0.34
EF4: Nitrogen deposition
0.15
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


Scotland
EF1: Nitrogen inputs
0.58
EF5: Nitrogen leaching and runoff
0.50
Fraction of nitrogen lost to leaching
0.32
EF3 for AWMS: pasture range and paddock
0.26
EF4: Nitrogen deposition
0.13
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

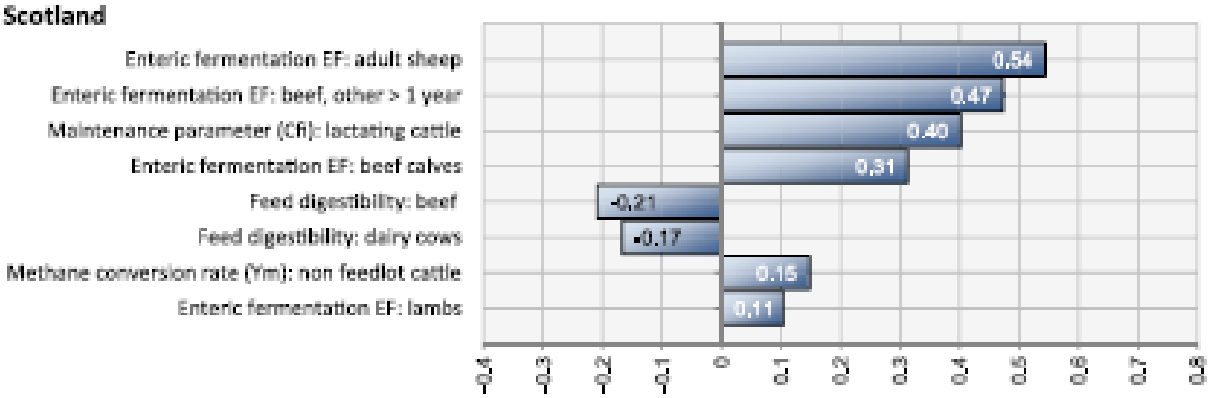

Northern Ireland
EF5: Nitrogen leaching and runoff
0.52
EF1: Nitrogen inputs
0.49
Fraction of nitrogen lost to leaching
0.34
EF3 for AWMS: pasture range and paddock
0.31
EF4: Nitrogen deposition
0.15
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Spearman Rank Correlation Coefficient



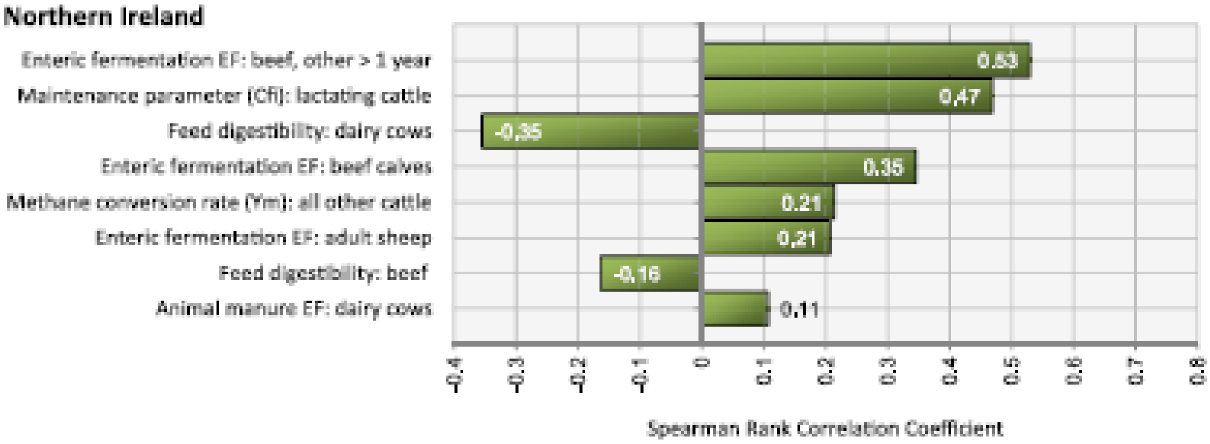
England



Wales



Scotland



Northern Ireland