Animal: An International Journal of Animal Bioscience

How do farm models compare when estimating greenhouse gas emissions from dairy cattle production?

--Manuscript Draft--

Manuscript Number:	ANIMAL-17-50252
Full Title:	How do farm models compare when estimating greenhouse gas emissions from dairy cattle production?
Short Title:	Dairy cattle farm model greenhouse gas comparison
Article Type:	Research Article
Section/Category:	5. Farming systems and environment
Keywords:	cattle; farm; model; greenhouse gas; dairy
Corresponding Author:	Nick Hutchings DENMARK
First Author:	Nicholas John Hutchings, PhD
Order of Authors:	Nicholas John Hutchings, PhD
	Şeyda Özkan Gülzari, PhD
	Michel de Haan
	Daniel Sandars
Manuscript Region of Origin:	DENMARK
Abstract:	The European Union (EU) Effort Sharing Regulation will require a 30% reduction in greenhouse gas (GHG) emissions from the sectors not included in the European Emissions Trading Scheme, including agriculture. This will require the estimation of baseline emissions from agriculture, including dairy cattle production systems. To support this process, four farm-scale models were benchmarked with respect to estimates of greenhouse gas (GHG) emissions from six dairy cattle scenarios; two climates (cool/dry and warm/wet) x two soil types (sandy and clayey) x two roughage production systems (grass only and grass/maize). The milk yield per cow (7000 kg Energy-corrected milk (ECM) year-1), follower:cow ratio (1:1), manure management system and land area were standardised for all scenarios. Potential yield and application of available N in fertiliser and manure were standardised separately for grass and maize. Significant differences between models were found in GHG emissions at the farm-scale and for most contributory sources, although there was no difference in the ranking of source magnitudes. The difference between the models with the lowest and highest GHG emission intensities, averaged over the six scenarios (0.08 kg CO2e (kg ECM)-1), was similar to the difference between the scenarios with the lowest and highest emission intensities (0.09 kg CO2e (kg ECM)-1), averaged over the four models, indicating that if benchmarking is to contribute to the quality assurance of emission estimates, there needs to be further discussion between modellers, and between modellers and those with expert knowledge of individual emission sources, concerning the nature and detail of the algorithms needed. Even though key production characteristics were standardised in the scenarios, there were still significant differences between models in the milk production ha-1 and the amounts of N fertiliser and concentrate feed imported. This was because the models differed both in their description of biophysical responses/feedback mechanisms and in the extent to which management functions were internalised. This shows that benchmarking farm models for dairy cattle systems will be more difficult than for those agricultural production systems where feedback mechanisms are less pronounced.
Suggested Reviewers:	Alan Rotz US Department of Agriculture Al.Rotz@ars.usda.gov Dairy farm systems modellerWorks with the development and use of models to evaluate alternative technologies and management strategies on integrated farming

	systems for dairy or beef production.
	Richard Eckard University of Melbourne rjeckard@unimelb.edu.au Research areas: - Greenhouse gas emissions from agricultural systems - mainly livestock (methane, nitrous oxide) - Nitrogen cycling in intensive grazing systems (nitrogen, ammonia, nitrate, volatilisation, denitrification, leaching) - Whole farm systems modelling of climate change impacts, adaptation and mitigation strategies (Production, nutrient cycling and emissions)
	Lawrence Shalloo Teagasc Food Research Centre Moorepark Laurence.Shalloo@Teagasc.ie Dairy farm systems modeller who has reviewed farm scale models of greenhouse gas emissions
Opposed Reviewers:	

Manuscript

How do farm models compare when estimating greenhouse gas emissions from dairy cattle production?

N.J.Hutchings[1], Ş. Özkan Gülzari [2,a], M. de Haan [3] and D. Sandars [4]

[1] *Department of Agroecology, Aarhus University, Blichers Allé 20, P.O. Box 50, Tjele, 8830 Denmark*

[2] *Department of Animal and Aquacultural Sciences, Faculty of Veterinary Medicine and Biosciences, Norwegian University of Life Sciences (NMBU), P.O. Box 5003, Ås, 1430 Norway*

[3] *Wageningen UR, Livestock Research, P.O. Box 338 Wageningen, 6700AH, The Netherlands*

[4] *School of Water, Energy, and Environment, Cranfield University, Bedford, MK43 0AL UK*

[a] *Present address: Norwegian Insitute of Bioeconomy Research, P.O. Box 115, Ås 1431 Norway*

Corresponding author: Nicholas Hutchings. Email: nick.hutchings@agro.au.dk

Short title: Comparing dairy cattle farm model greenhouse emissions

Abstract

The European Union (EU) Effort Sharing Regulation will require a 30% reduction in greenhouse gas (GHG) emissions from the sectors not included in the European Emissions Trading Scheme, including agriculture. This will require the estimation of baseline emissions from agriculture, including dairy cattle production systems. To support this process, four farm-scale models were benchmarked with respect to estimates of greenhouse gas (GHG) emissions from six dairy cattle scenarios; two climates (cool/dry and warm/wet) x two soil types (sandy and clayey) x two roughage production systems (grass only and grass/maize). The milk yield per cow (7000 kg Energy-corrected milk (ECM) year^{-1}), follower:cow ratio (1:1), manure management system and land area were standardised for all scenarios. Potential yield and application of available N in fertiliser and manure were standardised separately for grass and maize. Significant differences between models were found in GHG emissions at the farm-scale and for most contributory sources, although there was no difference in the ranking of source magnitudes. The difference between the models with the lowest and highest GHG emission intensities, averaged over the six scenarios (0.08 kg CO_2e (kg ECM)$^{-1}$), was similar to the difference between the scenarios with the lowest and highest emission intensities (0.09 kg CO_2e (kg ECM)$^{-1}$), averaged over the four models, indicating that if benchmarking is to contribute to the quality assurance of emission estimates, there needs to be further discussion between modellers, and between modellers and those with expert knowledge of individual emission sources, concerning the nature and detail of the algorithms needed. Even though key production characteristics were standardised in the scenarios, there were still significant differences between models in the milk production ha^{-1} and the amounts of N fertiliser and concentrate feed imported. This was because the models differed both in their description of biophysical responses/feedback mechanisms and in the extent to which management functions were internalised. This shows that benchmarking farm models for dairy cattle systems will be more difficult than for those agricultural production systems where feedback mechanisms are less pronounced.

Keywords: cattle, farm, model, greenhouse gas

Implications

If farm scale models of GHG emissions are to be useful in the more stringent regulatory environment in Europe, there needs to be further discussion between modellers, and between modellers and those with expert knowledge of individual emission sources, concerning the nature and detail of the algorithms used. Benchmarking can help maintain the quality of such models but feedback mechanisms exist within ruminant livestock systems that will make this more difficult than for other agricultural production systems.

Introduction

Globally, the livestock sector accounts for 14.5% of human-caused greenhouse gas emissions (GHG), producing 7.1 Gt of carbon dioxide equivalent (CO_2e) emissions year^{-1}, of which dairy farming contributes about 20% (Hagemann *et al.*, 2012). European dairy production is about 150 million tonnes of milk (European Dairy Association, 2016) and accounts for about 14% of the value of all agricultural production (https://ec.europa.eu/agriculture/milk_en). However, it also accounts for about one third of GHG emissions from the European livestock sector (Bellarby *et al.*, 2013) The sources of direct GHG emissions are methane (CH_4) from enteric fermentation and manure management and nitrous oxide (N_2O) from manure management and the soil. In addition, there are indirect GHG emissions in the form of N_2O, resulting from the nitrification and partial denitrification of reduced forms of nitrogen (N) that occur off-farm, either as a result of the atmospheric deposition of N from ammonia (NH_3) volatilization from manure management and the soil, or from nitrate (NO_3^-) leaching from the soil (IPCC, 2006).

Hitherto, there has been limited pressure to reduce GHG emissions from agriculture, although there is increased interest from the food retail sector concerning their GHG emissions and that of their supply chains (e.g. Tesco PLC, 2016). However, the European Union (EU) is currently in the process of supplementing its Effort Sharing Decision (European Commission, 2009) with an Effort Sharing Regulation (ESR; Erbach, 2016) that by 2030, will reduce by 30% the GHG emissions from the sectors not included in the European Emissions Trading Scheme (agriculture, transport, buildings, small industry and waste). The agreement will place a heavier burden on the wealthier Member States and impose national Annual Emission Allocations but will allow some flexibility concerning the distribution of reduction burden between sectors and allow limited transfer or trading of Annual Emission Allocations. How the ESR will be implemented in individual Member States is unclear, including the proportion of the emission reduction allocated to agriculture and the extent to which there is the ability and willingness to utilise the flexibility mechanisms. However, since the ESR contains reduction targets for EU member states that range from 0 to 40%, significant reductions seem likely to be demanded from agriculture, especially for more wealthy Member States with large agricultural sectors. The extent to which Member States choose to allocate reduction targets to individual agricultural production sectors or to individual farms has also yet to be decided.

Measurements of GHG emissions are not currently available at the farm scale and given the technical and financial challenges (Brentrup *et al.*, 2000, McGinn, 2006) it seems unlikely that this situation will change in the near future. Consequently, estimates of GHG emissions from agriculture for the farm scale and above are obtained by modelling. Ruminant livestock farms in general, and dairy cattle farms in particular, typically rely heavily on on-farm crop production to supply animal feed. This leads to a substantial internal cycling of nutrients (Jarvis *et al.*, 2011), feedback effects between farm components (livestock, manure management etc.) and difficulty in obtaining the information concerning feed intake necessary to calculate the major sources of GHG emissions. As a consequence, it is appropriate to rely on whole-farm systems models (Crosson *et al*., 2011).

A number of whole-farm cattle systems models have been developed to address this situation (Del Prado *et al.*, 2013, Kipling *et al.*, 2016). At present, these models have mainly been used for exploratory purposes e.g. Vellinga *et al.* (2011), for which plausibility is an adequate criteria for the form of response functions and the quality of inputs and parameters. Exploration will remain a useful function but in the future, farm-scale models will also need to operate within an environment in Europe in which there is regulatory or commercial pressure to reduce emissions and in which the quality of emission inventories at all scales is likely to be subject to increased scrutiny. Comparing the results from different models when used to simulate standard scenarios (benchmarking) can contribute to the quality assurance or review processes.

In order to achieve target-based reductions in GHG emissions, such as those proposed in the ESR, there is a need to establish baseline emissions i.e. emissions prior to the implementation of abatement measures. In the study reported here, we quantify the differences between four farm-scale models in the GHG emissions using six standard scenarios of dairy cattle production and identify the differences in the structure and function of the models that give rise to these differences.

Material and methods

The models used were DairyWise, developed in The Netherlands (Schils *et al.*, 2007), FarmAC, developed as part of an EU project (Hutchings and Kristensen, 2015), HolosNor, developed in Norway (Bonesmo *et al.*, 2012), and SFARMMOD, developed in the United Kingdom (Annetts and Audsley, 2002). DairyWise and HolosNor are specifically dedicated to dairy farming whereas FarmAC and SFARMOD can simulate a wider range of farm types. The choice of models used depended on who could obtain funding via the Modelling European Agriculture with Climate Change for Food Security (MACSUR) project (www.macsur.eu). A brief background to each model used in the current comparison study is given in Supplementary Material. The order of the models is alphabetical with no intention to rank them. Emissions are expressed in kg CO_2e year^{-1} and CO_2e (kg ECM^{-1}; i.e. emissions intensity). The models varied in the GHG sources included. Not all models could simulate off-farm GHG emissions, such as pre- or post-chain emissions. Nor could all models simulate emissions associated with the use of farm machinery or the sequestration of carbon (C) in the soil, so these were omitted from the comparison. Global warming potentials (GWP) of CH_4 and N_2O are 28 and 265 times higher than that of CO_2, respectively, for a given 100 year time horizon (Myhre *et al.*, 2013).

Scenarios

Each model simulated eight scenarios within a factorial design consisting of two climates, two soil types, and two feeding systems. The two climates were cool with moderate rainfall (Wageningen, The Netherlands) and warm with high rainfall (Santander, Spain). The Cool climate had a mean annual temperature of 9.6 ˚C and a mean annual precipitation of 757 mm. The Warm climate had a mean annual temperature 14.3 ˚C and a mean annual precipitation of 1268 mm. The characteristics of the Sandy soil were 60% sand, 10% silt, 30% clay and the Clayey soil were 10% sand, 45% silt, 45% clay. For both soil types, the pH >6, <7.5 and soil depth was 1 metre. For HolosNor, the maximum permissible clay content allowed by the model (35%) was used (A. O. Skjelvåg, Ås, 2016, personal communication).

The choice of scenarios was intended to provoke noticeable responses from the models whilst remaining within the range of conditions for European dairy production. The choice of climates was also determined by the need to access advice concerning climate-related farm management information. Grass has an energy:protein ratio that is sub-optimal for effective utilisation of the protein for milk production, so must be supplemented with an energy-rich feed when formulating diets (Özkan and Hill, 2015). This is commonly provided using either an imported cereal or on-farm maize silage, so two cropping systems were simulated, one consisting of grass only and other of grass and maize silage.

The interested partners agreed a set of standardised farm structure and management characteristics and parameters (Table 1). The emission intensity of milk production decreases with increasing annual milk production per cow (Casey and Holden, 2005, Gerber *et al.*, 2011), so it was necessary to standardise this factor. To avoid excessive externalising of GHG emissions through high imports of energy concentrates and to be relevant for as much of European dairy production as possible, we chose to simulate a production system with a moderate production of 7000 kg ECM cow^{-1} year^{-1}, rather than one designed to be typical for the two climates chosen. Typical farms in the relevant regions of Netherlands and Spain would produce about 7400 and 8400 kg ECM cow^{-1} year^{-1}.

Table 1 here

Complete standardisation of scenarios was not possible as all models required additional model-specific inputs or parameters. To internalize model responses, the exchange of material with off-farm systems was minimized. This meant that within realistic constraints (e.g. maintaining a realistic balance between energy and protein in cattle diets), the amount of imported animal feed and manure and the export of silage and manure was minimised. Since the milk yield per cow, the weight of the mature dairy cows and the number of young stock per mature dairy cow were standardised, the number of livestock that could be carried on the farm was determined by each model's prediction of (i) the diet necessary to achieve the specified milk yield and growth of immature livestock; and (ii) the capacity of the farm to produce roughage feed. HolosNor required the number of animals as an input; therefore, the number of animals in each scenario was inputted to HolosNor from FarmAC.

The statistical significance of the differences between models for the selected management variables and the estimated GHG emissions was determined using the Friedman test (Friedman, 1940), followed by the post-hoc Nemenyi test (Nemenyi, 1963). The analysis was undertaken using the Friedman.test and posthoc.friedman.nemenyi.test function from the PMCMR package (Pohlert, 2014) of R programming language.

Results

Differences between scenarios

The emission intensities for the different scenarios, averaged across models, are shown in Table 2. There were systematic differences between the grass only and grass/maize systems, with the grass only system required more concentrate feed, carried a higher livestock number and received more N fertiliser. The enteric CH_4 emissions were lower for the grass/maize system than the grass only. Manure CH_4 emissions varied little across scenarios whereas manure N_2O emission tended to be lower in the warm climate. The field N_2O emissions were similar for all scenarios. Nitrous oxide emissions associated with NH_3 volatilisation were slightly lower for the grass/maize system. Nitrous oxide emissions associated with NO_3^- leaching were greatest for the sandy soil than the clayey soil. The total GHG emission intensity was around 4% greater for the grass only system (1.11 kg CO_2e (kg ECM)$^{-1}$) than for the grass/maize (1.07 kg CO_2e (kg ECM)$^{-1}$), and greater for the cool climate (1.12 kg CO_2e (kg ECM)$^{-1}$) than the warm (1.07 kg CO_2e (kg ECM)$^{-1}$). The range of emission intensities (direct + indirect) was 0.09 kg CO_2e (kg ECM)$^{-1}$, the highest being the cool climate, sandy soil and grass only, and the lowest the warm climate, sandy soil and grass + maize.

Table 2 here

Production characteristics

DairyWise predicted a significantly higher number of dairy cows could be maintained than the other models (Fig. 1A). This was not due to lower values for the DM intake necessary to achieve the prescribed production; cow DM intake was on average 16.5, 15.6, 17.6 and 16.0 kg day^{-1} for DairyWise, FarmAC, HolosNor and SFARMOD respectively and for the followers, 6.0, 5.7, 7.1 and 4.8 kg day^{-1} respectively. The average milk production values ranged from 10413 litres ha^{-1} for DairyWise to 8750 litres ha^{-1} for HolsNor. The variation between scenarios was greatest for FarmAC (HolosNor used the same livestock numbers as FarmAC). There were significant differences between models in the amounts of concentrate feed imported (Fig. 1B), reflecting the differences in the diet predicted or considered necessary to achieve the target milk production specified. There were also large differences between models in the extent to which the feed import varied between scenarios. The area dedicated to maize silage production on grass/maize farms was significantly lower for SFARMMOD than for the other models (Fig. 1C). Note that for DairyWise, the area would have been higher, had the model not included a cap of 20% of field area that could be allocated to maize cultivation. There were significant differences between models in the amounts of fertiliser N applied (Fig. 1D).

Fig 1 here

Farm-scale GHG emissions and emissions intensity

Total GHG emissions expressed on an area basis were highest in DairyWise (Fig. 2A), significantly so in relation to SFARMMOD. However, this mainly reflects the significantly higher number of livestock predicted by DairyWise. When expressed in terms of an emission intensity, the differences between models were reduced, although there was a significant difference between FarmAC and both DairyWise and SFARMMOD (Fig. 2B). The range of the mean and median emission intensities was 0.08 and 0.10 kg CO_2e (kg ECM)$^{-1}$ respectively. Across scenarios, the range of emission intensities was greatest for DairyWise (0.16 kg CO_2e (kg ECM)$^{-1}$) and least for HolosNor (0.06 kg CO_2e (kg ECM)$^{-1}$). To remove the consequences of the higher livestock number predicted by DairyWise, the remaining emissions will be expressed as emissions intensities rather than on an area basis.

Figure 2 here

Direct and indirect greenhouse gas emissions

The enteric CH_4 emissions simulated by SFARMMOD were significantly greater than those by FarmAC and HolosNor (Fig. 3A). SFARMMOD estimates enteric CH_4 emissions from milk production, hence the lack of variation between scenarios. There were no significant differences between the estimates of field N_2O emissions from the different models (Fig. 3B). The manure CH_4 emissions estimated by SFARMMOD were lower than those of the other models, significantly so in the case of FarmAC (Fig. 3C). In contrast, for manure N_2O emissions (Fig. 3D), the emissions estimated by HolosNor were higher than those of the other models, significantly so in the case of DairyWise and SFARMMOD.

Figures 3 here

Indirect N_2O emissions resulting from NH_3 volatilisation and NO_3^- leaching (kg CO_2e (kg ECM)$^{-1}$ are shown in Fig. 4. There were large and significant differences between models for the N_2O emissions from both NH_3 volatilisation and NO_3^- leaching. The emissions estimated by HolosNor were significantly higher than for one or several models. For FarmAC, the emissions resulting from NO_3^- leaching were particularly variable between scenarios. The variation in GHG emissions between models is shown in Table 3. For each source, the mean of the emissions from the four models is subtracted from the emission from the individual model. Note the emission intensities are expressed in grams rather than kilograms CO_2e (kg ECM)$^{-1}$.

Figure 4 and Table 3 here

Discussion

Effect of scenarios

More concentrate feed was required to provide a balanced diet in the grass only system than the grass/maize system (Table 3). This meant that the total amount of feed available on the grass only farms was greater than for the grass/maize system, so more cows could be carried. Less fertiliser is applied to the grass/maize system than the grass only system, since the application of plant-available N specified for maize was lower than that for grass. The enteric CH_4 emissions were lower for the grass/maize system than the grass only, due to differences in diet. Manure CH_4 emissions were lower under the warn climate, due to the shorter housing period, although this was partially offset by the higher temperature, which led to a higher CH_4 emission per tonne of manure produced. The lower manure N_2O emission in the warm climate reflects the shorter housing season and consequent lower manure production. In contrast to CH_4 emissions, none of the models varied N_2O emissions according to temperature. The direct N_2O emissions were higher under the cool climate, as more excreta passed through the manure management system, leading to gaseous N emissions which lowered the concentration of plant-available N. The total N applied was therefore greater than for the warm climate.

The N_2O emissions associated with NO_3^- leaching were greater for the sandy than clayey soil, due to the lower ability of the former to retain water. The difference was greatest for the warm climate, since the precipitation excess was greatest here. The higher total GHG emissions for the grass only system than for the grass/maize system reflect the higher contributions from a number of sources, but especially enteric CH_4 emissions. The lower total GHG emissions in the warm climate compared to the cold reflect the lower emissions associated with manure management.

The total GHG emission intensities calculated here are similar to those found for Western Europe by Gerber *et al.* (2013) (once pre- and post-farm emissions are discounted), for Tasmania by Christie *et al.* (2011) and for Ireland by Casey and Holden (2005) (at the area requirement found here of 0.92 and 0.95 m^2 (kg ECM)$^{-1}$ for the cool and warm climates respectively). In contrast, the values were lower than the 1.2 kg CO_2e (kg ECM)$^{-1}$ found for Portuguese dairy farms by Pereira and Trindade (2015) and higher than the 0.83 and 0.73 kg CO_2e (kg ECM)$^{-1}$ found by O'Brien *et al.* (2011) when using the IPCC (2006) methodology with default and local parameterisation respectively. The separate contributions of CH_4 and N_2O found here (means of 0.67 and 0.26 kg CO_2e (kg ECM)$^{-1}$ respectively) were, however, higher than those found by Gerber *et al.* (2011) (0.54 and 0.24 kg CO_2e (kg ECM)$^{-1}$ respectively, after adjusting to the GWP for CH_4 and N_2O of Myhre *et al.* (2013).

Differences in production characteristics

The scenario specifications defined key production characteristics and yet achieving complete standardisation of farm management was not possible. The models differed both in their description of biophysical responses/feedback mechanisms and in the extent to which management functions were internalised. For example, when estimating the livestock number that could be carried on the farm, the DairyWise predictions were 15% higher than the other models (Fig. 1A). This occurred despite the major drivers of production (DM intake, import of concentrate feed and available N used for crop production) being similar or the same as the other models. To achieve an appropriate feed ration on the grass only farms, all models predicted it was necessary to import cereal feed. This import of feed increases the number of livestock that can be carried on the farm. Since maize silage has a higher nutritional value than grass, an appropriate feed ration could be more easily achieved from within the farms' resources when maize silage was available on the farm. Consequently, three of the four models found the need to import cereal-based feed was lower for the grass/maize system than for the grass only system and hence fewer livestock were carried (Fig. 1B); the exception being DairyWise. In DairyWise, the maximum percentage of the area of maize silage (20%) permitted is embedded in the model and corresponds to the derogation obtained by the Netherlands under the EU Nitrates Directive (European Commission, 1991 and 2014), so a higher import of concentrates is necessary to achieve an appropriate feed ration. Even the remaining models show substantial differences in the area allocated to maize silage production (Fig. 1C), reflecting the differences in the definition of an appropriate feed ration and the maize silage production predicted per unit area. This highlights a major difference between farm-scale models and those of individual farm components such as crops; the latter are commonly driven by external management variables whereas these are internalised to a varying extent within the farm-scale models.

Finally, the application of N fertiliser varied between models (Fig. 1D). Since the total amount of plant-available N applied was prescribed here and were different for grass and maize, the differences in the application of N fertilizer reflect the differences between models in the estimation of the plant-availability of N in the animal manure, and for grass/maize system, the relative areas allocated to grass and maize cultivation. This in turn reflects differences in the N losses occurring in the manure management system. The farm characterisation specified a higher input of plant-available N to grassland than to maize, so differences between models in the areas used to produce maize silage also lead to differences in the farm-scale demand for fertiliser N.

Differences in greenhouse gas emissions

Average predicted total GHG emissions per farm were highest for DairyWise (Fig. 2A). Since milk yield per cow was prescribed, the differences in GHG emissions can be accounted mainly by differences in the number of livestock that the models predicted could be supported on the farms, hence the differences between models decrease when emissions are expressed as emission intensities (Fig. 2B). The variation in enteric CH_4 emissions (Fig. 3A) has complex origins. The models differed in the methods used to determine the quantity and quality of feed appropriate to achieve the specified milk production per cow. Since pasture quality is predicted by DairyWise, the feed grass quality could not be standardised. This means there were differences between models in the quantities and qualities of fresh grass, grass silage and maize silage fed. Finally, there were differences in methods used to model enteric CH_4 emissions, which varied from varying emission factors per feedstuff (DairyWise), through the IPCC methodology (FarmAC, HolosNor), to a fixed factor based on milk production (SFARMMOD). The differences between estimates of N_2O emissions from the soil were not significant (Fig. 3B), but this was due to the substantial variation between models in their response to the scenarios. All models use algorithms similar to those used by IPCC (2006) and so are driven by the total amount of N entering the soil. The input of plant-available N was prescribed here so the total N input was largely decoupled from the behaviour of the livestock and manure management modules. The estimates of the total N input to the soil differed between models, since differences in the estimated loss of N in the manure management system meant that they differed in their assessment of the plant-availability of N in the manure ex storage. The lower the plant-availability in the manure, the higher the total manure N input. Furthermore, the total plant-available N application to grass was prescribed to be higher than that to maize, so differences between models in the allocation of land to these two crops affected the farm scale input of N to the soil for the grass/maize systems.

The differences in GHG emissions from manure (Fig. 3C and 3D) reflect differences in the management (see Farm management) and the throughput of manure dry matter (DM) and N, resulting from differences in the methods used to estimate DM and N excretion. The significant differences in indirect GHG emissions associated with NH_3 volatilisation (Fig. 4A) reflect differences in assumptions made or the methodology used. In particular, in the DairyWise simulations, a high DM content of the applied slurry was assumed, leading to high field NH_3 emissions. In the FarmAC simulations, a lower DM content was assumed and in SFARMMOD, a constant factor independent of DM. The low indirect emissions of N_2O associated with NO_3^- leaching predicted by DairyWise (Fig. 4B) is because it simulated a large loss of N via denitrification on the clayey soil. The small effect of soil type on the HolosNor simulations were because this model uses a leaching fraction that is not sensitive to soil type. In contrast, FarmAC was highly sensitive to soil type, especially in the warm climate due to the greater precipitation excess (difference between precipitation and evapotranspiration).

Predicting GHG emission intensities

The total emission intensities calculated by the different models were similar but this disguised differences between estimates of all the contributory emissions (Table 3). Nevertheless, all models indicated that enteric CH_4 was the major source, followed by soil N_2O emissions, and that the two together contributed more than half the total emissions. This would be expected from earlier investigations (FAO, 2010, Gerber *et al.*, 2011). Furthermore, all models ranked the importance of the remaining sources in the same order; manure CH_4 > indirect emissions > manure N_2O. This is important, since the ranking of targets for mitigation measures is a common reason for constructing such models (Cullen and Eckard, 2011, Del Prado *et al.*, 2013, Eory *et al.*, 2014). However, there were often significant differences between models in the estimated emission from a given source, as a result of differences in the relationships used to estimate GHG emissions, their parameterisation or the production characteristics driving those relationships.

Variation between scenarios might be expected to increase with model complexity, since this should increase the capacity to reflect the effect of different management strategies (Beukes *et al.*, 2011). Cullen and Eckard (2011) estimated GHG emissions for 4 locations in Australia and found the emissions estimated using the complex, dynamic model DairyMod (Johnson *et al.*, 2008) to be between +10% and -30% of the values estimated by an inventory method, depending on location. The majority of the variation between the two methods arose from differences between locations in the direct and indirect N_2O emissions predicted by the complex model. In the current study, the range of emission intensities, relative to the model returning the lowest estimate, was 4-9% for the cold climate and 13-16% for the warm climate. The lower variation found in this study is probably because the representation of the two dominant emission processes (enteric CH_4 and soil N_2O emissions) was in all models based to varying degrees on that of the IPCC (2006) methodology.

In O'Brien *et al.* (2011), the use of locally-determined rather than default parameters for the IPCC (2006) methodology led to a reduction in estimated GHG emissions of about 13%. In this study, the emission factors in FarmAC and HolosNor were adjusted to the IPCC (2006) default values for the relevant climate whereas the parameter values are not climate-sensitive in DairyWise and SFARMOD. Since the latter two models were developed in The Netherlands and UK respectively, this may explain the larger variation between the model emission estimates for the warm climate.

Conclusions

The difference between the models with the lowest and highest GHG emission intensities, averaged over the six scenarios (0.08 kg CO_2e (kg ECM)$^{-1}$), was similar to the difference between the scenarios with the lowest and highest emission intensities (0.09 kg CO_2e (kg ECM)$^{-1}$), averaged over the four models. Furthermore, the differences in the emission intensities between model estimates for most individual sources were proportionately larger than at the farm scale but without any consistent ranking of the models. The first conclusion is that if benchmarking is to contribute to the quality assurance of emission estimates, there needs to be further discussion between modellers, and between modellers and those with expert knowledge of individual emission sources, concerning the nature and detail of the algorithms needed; a process that is similar to that undertaken for ammonia emission modelling (www.eager.ch, Reidy *et al.*, 2008). This process is particularly relevant for those agriculturally-intensive Member States facing ambitious reduction targets within the ESR, since the potentially high costs of mitigation measures may justify more detailed modelling of individual sources (e.g. as is the case in The Netherlands; Bannink *et al.*, 2011). Even though key production characteristics were standardised in the scenarios used here, there were still significant differences between models in the milk production ha^{-1} and the amounts of N fertiliser and concentrate feed imported. This was because the models differed both in their description of biophysical responses/feedback mechanisms and in the extent to which management functions were internalised. The second conclusion is that benchmarking farm models for ruminant livestock systems will be more difficult than for other agricultural production systems, where feedback mechanisms are less pronounced.

Acknowledgements

This paper was supported by the FACCE-JPI knowledge hub Modelling European Agriculture with Climate Change for Food Security (MACSUR). National funding was received from the Norwegian Research Council and BBSRC (BB/N00485X/1 and BB/K010301/1 projects). Authors acknowledge the financial support from the European Commission (AIR3-CT94-1584, ECFARM project), UK Government Department for Agriculture and Rural Affairs (WA0801, MEASURES project), Ministry of Agriculture Fisheries and Food/Biotechnology and Biological Sciences Research Council who funded parts of the development of SFARMMOD. Thanks also to Jordi Doltra for his insight into dairy farm management in Northern Spain, Arne Oddvar Skjelvåg for preparing the soil and climate data for HolosNor simulations, and Bente

Aspeholen Åby, Sissel Hansen and Tonje Storlien for sharing their experiences with HolosNor.

References

Annetts JE and Audsley E 2002. Multiple objective linear programming for environmental farm planning. Journal of the Operational Research Society 53, 933-943.

Bannink A, van Schijndel MW and Dijkstra J 2011. A model of enteric fermentation in dairy cows to estimate methane emission for the dutch national inventory report using the IPCC Tier 3 approach. Animal Feed Science and Technology 166-67, 603-618.

Bellarby J, Tirado R, Leip A, Weiss F, Lesschen JP and Smith P 2013. Livestock greenhouse gas emissions and mitigation potential in Europe. Global Change Biology 19, 3-18.

Beukes PC, Gregorini P and Romera AJ 2011. Estimating greenhouse gas emissions from new zealand dairy systems using a mechanistic whole farm model and inventory methodology. Animal Feed Science and Technology 166-67, 708-720.

Bonesmo H, Skjelvag AO, Janzen HH, Klakegg O and Tveito OE 2012. Greenhouse gas emission intensities and economic efficiency in crop production: A systems analysis of 95 farms. Agricultural Systems 110, 142-151.

Brentrup F, Kusters J, Lammel J and Kuhlmann H 2000. Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. International Journal of Life Cycle Assessment 5, 349-357.

Casey JW and Holden NM 2005. The relationship between greenhouse gas emissions and the intensity of milk production in Ireland. Journal of Environmental Quality 34, 429-436.

Christie KM, Rawnsley RP and Eckard RJ 2011. A whole farm systems analysis of greenhouse gas emissions of 60 Tasmanian dairy farms. Animal Feed Science and Technology 166-67, 653-662.

Crosson P, Shalloo L, O'Brien D, Lanigan GJ, Foley PA, Boland TM, Kenny DA, 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. Animal Feed Science and Technology 166-67, 29-45.

Cullen BR and Eckard RJ 2011. Impacts of future climate scenarios on the balance between productivity and total greenhouse gas emissions from pasture based dairy systems in south-eastern Australia. Animal Feed Science and Technology 166-67, 721-735.

Del Prado A, Crosson P, Olesen JE and Rotz CA 2013. Whole-farm models to quantify greenhouse gas emissions and their potential use for linking climate change mitigation and adaptation in temperate grassland ruminant-based farming systems. Animal 7, 373-385.

Eory V, MacLeod M, Shrestha S and Roberts D 2014. Linking an economic and a life-cycle analysis biophysical model to support agricultural greenhouse gas mitigation policy. German Journal of Agricultural Economics 63, 133-142.

Erbach G 2016. Effort sharing regulation, 2021-2030. Limiting member states' carbon emissions. In European Parliamentary Research Service. http://www.europarl.europa.eu/RegData/etudes/BRIE/2016/589799/EPRS_BRI(2016)589799_EN.pdf

European Commission 1991. Council directive of 12 december 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official Journal of the European Communities No L 375/1.

European Commission 2009. Decision no 406/2009/ec of the European Parliament and of the Council of 23 april 2009 on the effort of member states to reduce their greenhouse gas emissions to meet the community’s greenhouse gas emission reduction commitments up to 2020. Official Journal of the European Union L 140/136 - 148.

European Commission 2014. Commission implementing decision of 16 may 2014 granting a derogation requested by the Netherlands pursuant to council directive 91/676/eec concerning the protection of waters against pollution caused by nitrates from agricultural sources (notified under document c(2014) 3103). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32014D0291

FAO 2010. Greenhouse gas emissions from the dairy sector. A life cycle assessment. UN Food and Agriculture Organisation, Rome, Italy.

Gerber P, Vellinga T, Opio C and Steinfeld H 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livestock Science 139, 100-108.

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A and Tempio G 2013. Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. UN Food and Agriculture Organisation, Rome, Italy.

Hagemann M, Ndambi A, Hemme T and Latacz-Lohmann U 2012. Contribution of milk production to global greenhouse gas emissions. Environmental Science and Pollution Research 19, 390-402.

IPCC 2006. 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme (eds. S Eggleston, L Buendia, K Miwa, T Nagara and K Tanabe), Japan.

Jarvis SC, Hutchings NJ, Brentrup F, Olesen JE and van der Hoek K 2011. Nitrogen flows in farming systems across europe. In European nitrogen assessment (eds. MA Sutton, CM Howard, JW Erisman, G Billen, A Bleeker, P Grennfelt, Hv Grinsven and B Grizzetti), pp. 211-218, Cambridge University Press.

Johnson IR, Chapman DF, Snow VO, Eckard RJ, Parsons AJ, Lambert MG and Cullen BR 2008. Dairymod and ecomod: Biophysical pasture-simulation models for australia and new zealand. Australian Journal of Experimental Agriculture 48, 621-631.

Kipling RP, Bannink A, Bellocchi G, Dalgaard T, Fox NJ, Hutchings NJ, Kjeldsen C, Lacetera N, Sinabell F, Topp CFE, van Oijen M, Virkajarvi P and Scollan ND 2016. Modeling European ruminant production systems: Facing the challenges of climate change. Agricultural Systems 147, 24-37.

McGinn SM 2006. Measuring greenhouse gas emissions from point sources in agriculture. Canadian Journal of Soil Science 86, 355-371.

Myhre G, D. , Shindell FM, Bréon W, Collins J, Fuglestvedt J, Huang D, Koch JF, Lamarque DL, Mendoza B, Nakajima T, Robock A, Stephens G, T. T and Zhang H 2013. Anthropogenic and natural radiative forcing. In Climate change 2013: The physical science basis. Contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change (eds. TF Stocker, D Qin, GK Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, B V. and PM Midgley) Cambridge University Press, Cambridge, UK.

Nemenyi PB 1963. Distribution-free multiple comparisons. PhD thesis, Princeton University, USA.

O'Brien D, Shalloo L, Buckley F, Horan B, Grainger C and Wallace M 2011. The effect of methodology on estimates of greenhouse gas emissions from grass-based dairy systems. Agriculture Ecosystems & Environment 141, 39-48.

Özkan, Ş., Hill, J., 2015. Implementing innovative farm management practices on dairy farms: a review of feeding systems. Turk. J. Vet. Anim. Sci 39, 1–9.

Pereira J and Trindade H 2015. Impact of the intensity of milk production on ammonia and greenhouse gas emissions in Portuguese cattle farms. Spanish Journal of Agricultural Research 13.

Tesco PLC 2016. Our carbon footprint. https://www.tescoplc.com/tesco-and-society/sourcing-great-products/reducing-our-impact-on-the-environment/our-carbon-footprint/. Access date: 14 February 2017

Pohlert T 2014. The pairwise multiple comparison of mean ranks package (PMCMR) R package. http://CRAN.R-project.org/package=PMCMR.

Reidy B, Dammgen U, Dohler H, Eurich-Menden B, van Evert FK, Hutchings NJ, Luesink HH, Menzi H, Misselbrook TH, Monteny GJ and Webb J 2008. Comparison of models used for national agricultural ammonia emission inventories in Europe: Liquid manure systems. Atmospheric Environment 42, 3452-3464.

Schils RLM, de Haan MHA, Hemmer JGA, van den Pol-van Dasselaar A, De Boer JA, Evers AG, Holshof G, van Middelkoop JC and Zom RLG 2007. Dairywise, a whole-farm dairy model. Journal of Dairy Science 90, 5334-5346.

Vellinga TV, de Haan MHA, Schils RLM, Evers A and van den Pol-van Dasselaar A 2011. Implementation of GHG mitigation on intensive dairy farms: Farmers' preferences and variation in cost effectiveness. Livestock Science 137, 185-195.

Table 1. Standardised farm data

Category	Notes
Dairy cows	Mature live weight 600 kg, milk yield 7000 kg ECM cow^{-1} $year^{-1}$, diet: grass + concentrate or grass + maize silage + concentrate, grazing time: 16 hours day^{-1} during growing season*
Young animals	1 female:dairy cow, with male calves exported at birth, diet: grass + concentrate or grass + maize silage + concentrate, grazing time; 24 hours day^{-1} during growing season
Manure management	Livestock housing; freely-ventilated, fully slatted floor, manure storage; slurry tank with natural crust, manure application; broadcast spreader, no incorporation
Fields	Total area; 50 ha, irrigation; none
Crop potential DM yield (with irrigation if necessary)	Grass; cool climate: 10 tonnes ha^{-1} $year^{-1}$, warm climate: 8 tonnes ha^{-1} $year^{-1}$. Maize; cool climate: 14 tonnes ha^{-1} $year^{-1}$, warm climate: 18 tonnes ha^{-1} $year^{-1}$. Values were established after consultation with local experts.
N fertilisation	Grass; 275 kg plant-available N ha^{-1} $year^{-1}$. Maize 150 kg plant-available N ha^{-1} $year^{-1}$ **

* cool climate; May to September, warm climate; March to November

** Fertiliser type urea, with all fertiliser N considered plant-available. For animal manure, plant-available N was equal to the mineral N present. The total N application in manure was not permitted to exceed 250 kg N ha^{-1} $year^{-1}$ for permanent grassland and 170 kg N ha^{-1} $year^{-1}$ for maize silage. Manure was only exported if these application rates would otherwise be exceeded.

Table 2 Summary of results for the different scenarios

	Scenario*							
	CSG	CSM	CCG	CCM	WSG	WSM	WCG	WCM
	head							
Number of dairy cows	69	62	69	63	70	65	69	67
	t DM $year^{-1}$							
Imported concentrate feed	126	67	124	82	116	67	116	78
	ha							
Maize area	0	13	0	12	0	11	0	10
	kg ha^{-1} $year^{-1}$							
Fertiliser N	231	221	232	228	252	238	253	240
	kg CO_2e $(kg\ ECM)^{-1}$							
	Direct emissions							
Enteric CH_4	0.68	0.67	0.68	0.67	0.67	0.66	0.67	0.66
Manure CH_4	0.14	0.14	0.14	0.14	0.11	0.11	0.12	0.11
Manure N_2O	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.02
Field N_2O	0.27	0.25	0.26	0.24	0.18	0.17	0.18	0.17
	Indirect emissions							
Volatilization of NH_3	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Leaching of NO_3^-	0.03	0.03	0.02	0.02	0.03	0.03	0.02	0.02
	Total emissions							
Emissions intensity	1.17	1.14	1.16	1.14	1.12	1.08	1.12	1.08

* Cxx = Cool climate, Wxx = Warm climate, xSx = Sandy soil, xCx = Clayey soil, xxG = Grass only, xxM = Grass and maize.

Table 3. Variation between models in the direct and indirect GHG emissions.

Model	Enteric CH_4	Soil N_2O	Manure CH_4	Manure N_2O	Indirect	Direct + indirect
			gCO_2e (kg ECM)$^{-1}$			
DairyWise	0	-42	13	-7	0	-36
FarmAC	-23	33	48	0	-13	44
HolosNor	-8	-16	2	10	31	19
SFARMMOD	31	26	-63	-3	-17	-27
Mean of models	670	260	130	20	50	1130

Figure captions

Figure 1

The number of dairy cows (A), amount of concentrate feed imported (Mg DM year^{-1}) (B), area of maize on farms growing both grass and maize (ha) (C) and fertiliser N applied (kg ha^{-1} year^{-1}) (D). The boxplots show the data median and quartiles. Differences between models are not significantly different from one another if they share the same letter.

Figure 2

Total GHG emissions from all sources, expressed as a farm total (kg CO_2e year^{-1}) (A) and as an emission intensity (kg CO_2e (kg ECM)$^{-1}$) (B). The boxplots show the data median and quartiles. Differences between models are not significantly different from one another if they share the same letter.

Figure 3

Direct GHG emissions; enteric CH_4 emissions (A), soil N_2O emissions (B), manure CH_4 (C) and manure N_2O emissions (D) (kg CO_2e (kg ECM)$^{-1}$). The boxplots show the data median and quartiles. Differences between models are not significantly different from one another if they share the same letter.

Figure 4

Indirect N_2O emissions resulting from leaching of NO_3^- (A) and from volatilisation of NH_3 from manure management and field-applied manure (B) (kg CO_2e (kg ECM)$^{-1}$).

The boxplots show the data median and quartiles. Differences between models are not significantly different from one another if they share the same letter.

Figure 1

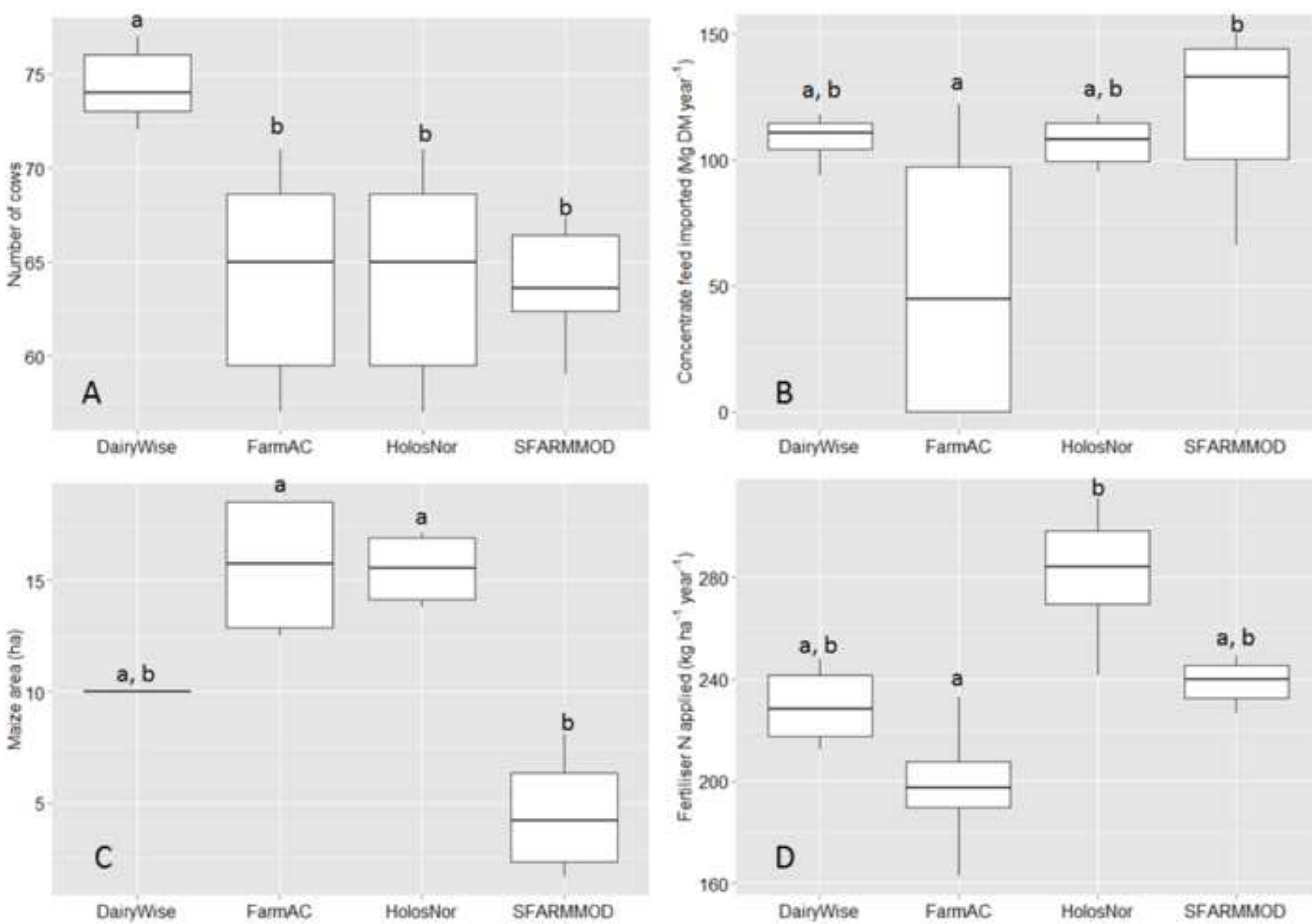

A
Number of cows
60
65
70
75
a
b
b
b
DairyWise
FarmAC
HolosNor
SFARMMOD
B
Concentrate feed imported (Mg DM year^{-1})
0
50
100
150
a, b
a
a, b
b
DairyWise
FarmAC
HolosNor
SFARMMOD
C
Maize area (ha)
5
10
15
a, b
a
a
b
DairyWise
FarmAC
HolosNor
SFARMMOD
D
Fertiliser N applied (kg ha^{-1} year^{-1})
160
200
240
280
a, b
a
b
a, b
DairyWise
FarmAC
HolosNor
SFARMMOD

Figure 2

Click here to download Figure Fig 2.tif

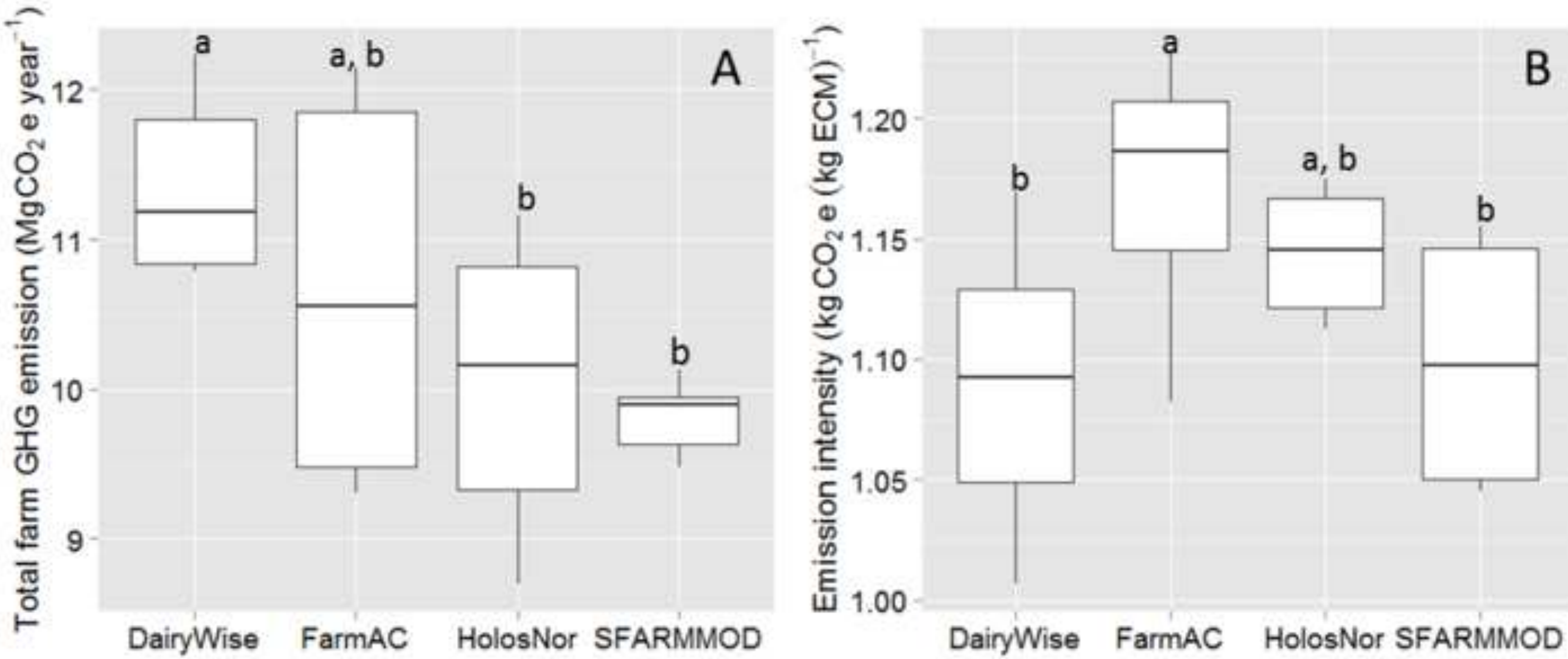


Figure 3 Click here to download Figure Fig 3.tif

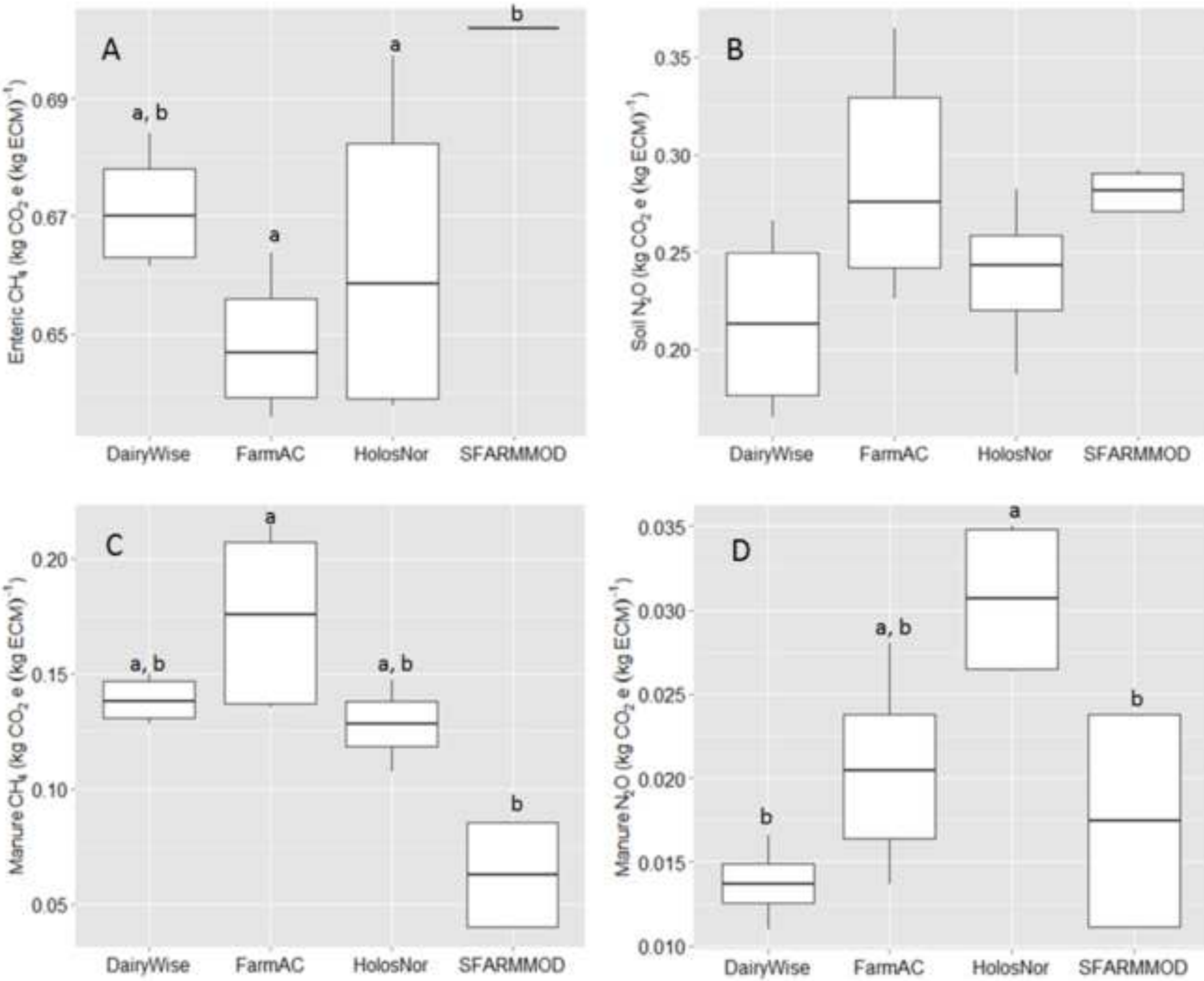
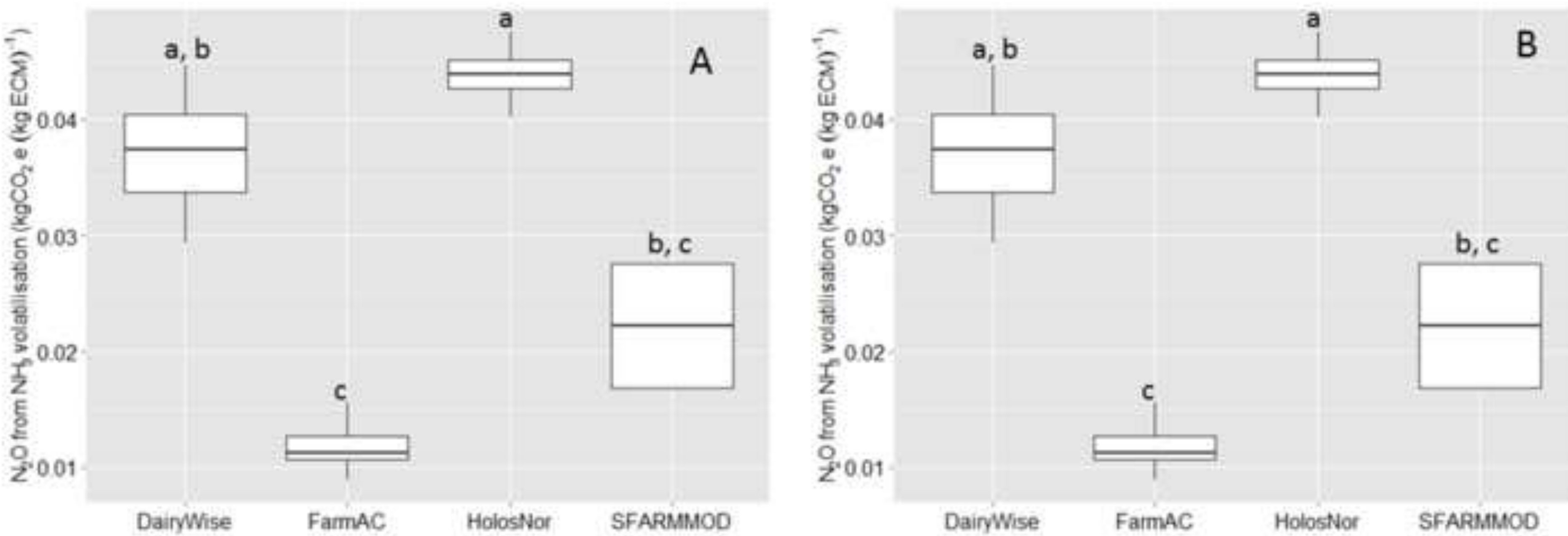


Figure 4

Click here to download Figure Fig 4.tif



How do farm models compare when estimating greenhouse gas emissions from dairy cattle production?

N.J.Hutchings, S. Özkan Gülzari, M. de Haan and D. Sandars

Models used

DairyWise

The DairyWise model includes all major subsystems of a dairy farm. The central component of DairyWise is the FeedSupply model, which meets the herd requirements for energy and protein, using home-grown feeds (grazed or cut grass, forage crops e.g. maize), maize silage and imported feed. The deficit between requirements and supply is imported as concentrates and roughage (Alem and Van Scheppingen, 1993, Schroder *et al.*, 1998, Zom *et al.*, 2002, Vellinga *et al.*, 2004, Vellinga, 2006, Schils *et al.*, 2007). Methane, N_2O, and CO_2 emissions are calculated in the sub model GHG emissions, which uses the emission factors from the Dutch emission inventories (Schils *et al.*, 2006). Methane emissions from enteric fermentation are calculated using different emission factors for concentrate, grass products, and maize (*Zea mays* L.) silage. The emission factors used to calculate CH_4 emissions from manure storage are those used in the MITERRA model (Velthof *et al.*, 2007), specific Dutch National Inventory Report calculations, according to IPCC. Direct N_2O emissions are related to manure management, N excreted during grazing, manure application, fertilizer use, crop residues, N mineralization from peat soils, grassland renewal, and biological N fixation. The emission factors are specified according to soil type and ground water level, with generally higher emissions on organic soils and wetter soils. Indirect N_2O emissions resulting from the partial denitrification of NO_3^- resulting from the oxidation of reduced N forms are calculated based on NH_3 volatilization and NO_3^- leaching. The emissions of NH_3 volatilised are calculated separately for animal housing, manure storage and field-applied manure and fertiliser. Nitrate leaching to ground water was calculated for sandy soils according to the NO_3^- leaching model of (Vellinga *et al.*, 2001). The amount of NO_3^- leached was related to the amount of soil mineral nitrogen (SMN) to a depth of 1 meter at the end of the growing season and soil type. The ground water table determined the partitioning of SMN in NO_3^- leaching and denitrification. The lower the groundwater table, the higher the proportion of NO_3^- leaching. For grassland, a basic SMN was calculated from the difference between applied and harvested N. In the case of grazing, additional SMN was calculated from urine excretions.

FarmAC

The FarmAC model simulates the flow of carbon (C) and N on arable and livestock farms, enabling the quantification of GHG emissions, N losses to the environment and C sequestration in the soil. It was constructed as part of the EU project AnimalChange (http://www.animalchange.eu/). It is intended to be applicable to a wide range of farming systems across the globe. The model is parameterised separately for each agro-climatic zone.

A static livestock model is used in which the user defines the average annual number of dairy cows, heifers and calves on the farm and the feed ration (including grazed forage). Ruminant livestock production is modelled using a simplified version of the factorial energy accounting system described in (CSIRO, 2007). Protein supply limitations on production are simulated using an animal N balance approach. Losses of C in CO_2 and CH_4 are simulated using apparent feed digestibility and IPCC (2006) Tier 2 methods, respectively.

Carbon and N in excreta are partitioned to grazed pasture in the same proportion as grazed DM contributes to total DM intake, with the remainder partitioned to the animal housing. Tier 2 methodologies are used for simulating flows in animal housing (CO_2 and NH_3), manure storage (CO_2, CH_4, N_2O, N_2 and NH_3) and for N_2O, N_2 and NH_3 emissions from fields. A dynamic model is used to simulate crop production and nutrient flows in the field. The dynamics of soil C are described using the C-Tool model (Taghizadeh-Toosi et al., 2014). A simple soil water model (Olesen and Heidmann, 1990) is used to simulate soil moisture content and drainage. Soil organic N degradation follows C degradation. Mineral N is not chemically speciated. The pool of mineral N is increased by the net mineralisation of organic N and by inputs of fertiliser and manure. It is depleted by leaching, denitrification and crop uptake. The N_2O emission associated with the modelled NH_3 volatiliseation and NO_3^- leaching were calculated using (IPCC, 2006). Crop production is determined by a potential production rate, moderated by N and water availability. The user determines the type, amount and timing of fertiliser and manure applications to each crop.

HolosNor

HolosNor was developed as a farm-scale model to calculate the GHG emissions produced from combined dairy and beef productions systems (Bonesmo *et al.*, 2012) in Norway. It is based on the Canadian Holos model (Little, 2008) utilising the IPCC methodology (IPCC, 2006) modified for Norwegian conditions. The GHGs accounted for in HolosNor are CH_4 emissions from enteric fermentation and manure, direct N_2O emissions from agricultural soils, indirect N_2O emissions resulting from NO_3^- leached, N in run-off and NH_3 volatilised. Both direct and indirect N_2O emissions include emissions from manure and synthetic fertiliser applications in soils.

The calculations of all emissions are explained in (Bonesmo *et al.*, 2012) in details based on Tier 2 approach. Here only the modification made to the model and input parameters to run the model are described. The ration consisted of grazed grass, grass silage (maize silage in the grass and maize system) grown on farm and concentrates. There was no crop production on the farm. Therefore, concentrates consisting of barley and soybean meal were purchased outside the farm. The CO_2e emissions associated with production of purchased concentrates were calculated from the mix of barley and soya that could provide the amount of energy and protein in the purchased concentrate (Bonesmo *et al.*, 2012). The amount of concentrates required was calculated using a regression model (B. Aspeholen Åby, Ås, 2016, personal communication) based on concentrate intake and forage requirement for different levels of milk production, as described in (Volden, 2013). Total net energy requirement (NE; MJ cow^{-1} day^{-1}) was calculated based on the IPCC (2006) recommendations considering maintenance, activity, lactation and pregnancy requirements. Total NE requirement was then converted to DM by taking into account the energy density of the feeds used (6 and 6.5 MJ NE (kg DM)$^{-1}$ for grass and maize silages, respectively) (http://feedstuffs.norfor.info/). Silage requirement per cow was then calculated by multiplying the total DM requirement by the silage proportion in the ration. By dividing the total farm silage requirement by the potential DM yield given as an input parameter (but corrected for fresh weight and feeding losses), the area to grow silage was computed. The remainder area was allocated for grazing. In the maize scenario, the above and below ground N residue concentration, yield ratio, and above and below ground residue rations were adjusted according to (Janzen *et al.*, 2003). Methane conversion factor for the warm climate was also adjusted according to IPCC guidelines, as the default values represented the cool climate (IPCC, 2006). In calculating the soil and weather data as one of the required input data, a 45% clayey soil for the Netherlands was found to be outside the normal variation, and therefore the clay content of 35% was applied (A. O. Skjelvåg, Ås, 2016, personal communication).

SFARMMOD

The Silsoe whole-FARM MODel is a linear programme (LP) that maximises long-run farm profit. The concept and structure of the arable farm model are described in (Audsley, 1981) with the mathematical structure fully described in (Annetts and Audsley, 2002). The latter paper details the extensions to model mixed arable and livestock systems. The main focus of the environmental burdens concerns the N cycle. Methane emissions were also included, but only from animal agriculture. Sources of information include inventories (Pain *et al.*, 1997, Sneath *et al.*, 1997, Chadwick *et al.*, 1999) and experimental data and mechanistic models (Scholefield *et al.*, 1991, Bouwman, 1996, Smith *et al.*, 1996, Chambers *et al.*, 1999, MAFF, 2000). Some could be used directly (e.g. indirect N_2O emissions associated with NH_3 volatilisation from animal houses), but others required considerable adaptation to meet the long-term needs of the LP framework (e.g. NO_3^- leaching) and to ensure that nutrient cycles are closed with no change in N storage in the soil (Williams *et al.*, 2002, Sandars *et al.*, 2003, Williams *et al.*, 2003).

Supplementary references

Alem vG and Van Scheppingen A 1993. The development of a farm budgeting program for dairy farm. In Proceedings XXV CIOSTA-CIGR V Congress, pp. 326-331.

Annetts JE and Audsley E 2002. Multiple objective linear programming for environmental farm planning. Journal of the Operational Research Society 53, 933-943.

Audsley E 1981. An arable farm model to evaluate the commercial viability of new machines or techniques. Journal of Agricultural Engineering Research 26, 135-149.

Bonesmo H, Skjelvag AO, Janzen HH, Klakegg O and Tveito OE 2012. Greenhouse gas emission intensities and economic efficiency in crop production: A systems analysis of 95 farms. Agricultural Systems 110, 142-151.

Bouwman AF 1996. Direct emission of nitrous oxide from agricultural soils. Nutrient Cycling in Agroecosystems 46, 53-70.

Chadwick DR, Sneath RW, Phillips VR and Pain BF 1999. A UK inventory of nitrous oxide emissions from farmed livestock. Atmospheric Environment 33, 3345-3354.

Chambers BJ, Lord EI, Nicholson FA and Smith KA 1999. Predicting nitrogen availability and losses following application of organic manures to arable land: Manner. Soil Use and Management 15, 137-143.

CSIRO 2007. Nutrient requirements of domesticated ruminants. CSIRO PUBLISHING, Collingwood, Australia.

IPCC 2006 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme IGES Japan

Janzen HH, Beauchemin KA, Bruinsma Y, Campbell CA, Desjardins RL, Ellert BH and Smith EG 2003. The fate of nitrogen in agroecosystems: An illustration using canadian estimates. Nutrient Cycling in Agroecosystems 67, 85-102.

Little S 2008 Holos, a tool to estimate and reduce greenhouse gases from farms: Methodology & algorithms for version 1.1.X. Agri-Food Canada. http://publications.gc.ca/pub?id=9.691658&sl=0

MAFF 2000 Fertiliser recommendations for agricultural and horticultural crops (RB209) London, UK

Pain B, Misselbrook T, Jarvis S, Chambers B, Smith K, Webb J, Phillips V, Sneath R and Demmers T 1997 Inventory of ammonia emission from UK agriculture London, UK

Sandars DL, Audsley E, Canete C, Cumby TR, Scotford IM and Williams AG 2003. Environmental benefits of livestock manure management practices and technology by life cycle assessment. Biosystems Engineering 84, 267-281.

Schils RLM, Verhagen A, Aarts HFM, Kuikman PJ and Sebek LBJ 2006. Effect of improved nitrogen management on greenhouse gas emissions from intensive dairy systems in the Netherlands. Global Change Biology 12, 382-391.

Schils RLM, de Haan MHA, Hemmer JGA, van den Pol-van Dasselaar A, De Boer JA, Evers AG, Holshof G, van Middelkoop JC and Zom RLG 2007. Dairywise, a whole-farm dairy model. Journal of Dairy Science 90, 5334-5346.

Scholefield D, Lockyer DR, Whitehead DC and Tyson KC 1991. A model to predict transformations and losses of nitrogen in UK pastures grazed by beef-cattle. Plant and Soil 132, 165-177.

Schroder JJ, Neeteson JJ, Withagen JCM and Noij IGAM 1998. Effects of N application on agronomic and environmental parameters in silage maize production on sandy soils. Field Crops Research 58, 55-67.

Smith JU, Bradbury NJ and Addiscott TM 1996. Sundial: A PC-based system for simulating nitrogen dynamics in arable land. Agronomy Journal 88, 38-43.

Sneath R, Chadwick D, Phillips V and Pain B 1997 A UK inventory of methane emissions from farmed livestock. MAFF, London, UK

Vellinga TV 2006. Management and nitrogen utilisation of grassland on intensive dairy farms. PhD Thesis, Wageningen, The Netherlands.

Vellinga TV, Van der Putten AHJ and Mooij M 2001. Grassland management and nitrate leaching, a model approach. Netherlands Journal of Agricultural Science 49, 229-253.

Vellinga TV, Andre G, Schils RLM and Oenema O 2004. Operational nitrogen fertilizer management in dairy farming systems: Identification of criteria and derivation of fertilizer application rates. Grass and Forage Science 59, 364-377.

Velthof GL, Oudendag DA and Oenema O 2007 Development and application of the integrated nitrogen model MITERRA-Europe. Alterra-rapport 1663.1. http://content.alterra.wur.nl/Webdocs/PDFFiles/Alterrarapporten/AlterraRapport1663.1.pdf

Volden H 2013 Yield level in milk production – feed and area requirement, Bioforsk Fokus 8: 42-44. (in Norwegian).

Williams AG, Sandars DL and Audsley E 2002 Framework to evaluate farm practices to meet multiple environmental objectives London, UK. Final report for Defra for Project Number WA 0801, London, UK.

Williams AG, Sandars DL, Annetts JE, Audsley E, Goulding KW, Leech P and Day W 2003. A framework to analyse the interaction of whole farm profits and environmental burdens. In Proceedings of EFITA 2003 4th Conference of the European Federation for information technology in Agriculture, Food and Environment, Debrecen, Hungary, pp. 492–498.

Zom R, Van Riel J, André G and Van Duinkerken G 2002 Predicted intake with the cow model. Praktijkonderzoek Veehouderij, Lelystad, The Netherlands (in Dutch)