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

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Short title: Comparing dairy cattle farm model greenhouse emissions

Abstract

The European Union (EU) Effort Sharing Regulation (ESR) will require a 30% reduction in greenhouse gas (GHG) emissions by 2030 compared to 2005 from the sectors not included in the European Emissions Trading Scheme, including agriculture. This will require the estimation of current and future emissions from agriculture, including dairy cattle production systems. Using a farm-scale model as part of a Tier 3 method for farm to national scales provides a more holistic and informative approach than IPCC (2006) Tier 2 but requires independent quality control. Comparing the results of using models to simulate a range of scenarios that explore an appropriate range of biophysical and management situations can support this process by providing a framework for placing model results in context. To assess the variation between models and the process of understanding differences, estimates of greenhouse gas (GHG) emissions from four farm-scale models (DairyWise, FarmAC, HolosNor and SFARMMOD) were calculated for eight dairy farming scenarios within a factorial design consisting of two climates (cool/dry and warm/wet) x two soil types (sandy and clayey) x two feeding systems (grass only and grass/maize). The milk yield per cow, follower:cow ratio, manure management system, N fertilisation and land area were standardised for all scenarios in order to associate the differences in the results with the model structure and function. Potential yield and application of available N in fertiliser and manure were specified 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 farm-scale GHG emissions, averaged over the four models, was 10.6 t carbon dioxide equivalents (CO_2e) ha^{-1} yr^{-1}, with a range of 1.9 t CO_2e ha^{-1} yr^{-1}. Even though key production characteristics were specified in the scenarios, there were still significant differences between models in the annual milk production ha^{-1} and the amounts of N fertiliser and concentrate feed imported. This was because the models differed in their description of biophysical responses and feedback mechanisms, and in the extent to which management functions were internalised. We conclude that comparing the results of different farm-scale models when applied to a range of scenarios would build confidence in their use in achieving ESR targets, justifying further investment in the development of a wider range of scenarios and software tools.

Keywords: dairy cattle, farm-scale, model, greenhouse gas

Implications

Farm-scale models can be used to document GHG emissions and predict the likely consequences of mitigation measures on both emissions and production. However, regulators and commercial organisations need assurance of the validity of their use. An inter-comparison of models should form part of this process.

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 over 150 million tonnes of milk and accounts for about 15% of the value of all European agricultural production (European Commission, 2017). However, it also accounts for about one third of GHG emissions from the European livestock sector (Bellarby *et al.*, 2013). The sources of direct on-farm 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 on-farm manure management and the soil, or from nitrate (NO_3^-) leaching from the fields on the farm (IPCC, 2006). Finally, changes to the amount of C stored in the soil can act as a source or sink for CO_2.

Hitherto, there has been limited regulatory 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 compared to 2005, 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. Member States that decide they need to reduce agricultural GHG emissions will need to choose a method of implementing reduction measures and how these will be documented in their national GHG inventories. This could include devolving the choice of measures and GHG accounting to individual farms, and the use of farm typologies in their national GHG accounting.

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 using the Tier 2 IPCC methodology. Member States will need to assess the cost and effectiveness of the mitigation measures needed to achieve the ESR reductions and report projected emissions (European Commission, 2013). As noted by Crosson *et al.* (2011), whole-farm systems models offer a more consistent approach than IPCC methodologies when assessing GHG emissions from such farms. This includes capturing feedback effects and allowing the consequences of mitigation measures on production and costs to be assessed.

A number of whole-farm cattle systems models have been developed (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 modelled results with empirical data is not currently possible at the farm scale, given the technical and financial challenges (Brentrup *et al.*, 2000, McGinn, 2006). Quality assurance or review processes can therefore benefit from the comparison of results from different models when used to simulate a range of scenarios (e.g. as in Özkan Gülzari *et al.*, 2017 and Veltman *et al.*, 2017). Deviations in the results from new models or new versions of existing models compared to earlier simulations with the same scenarios can be investigated to assess whether they are scientifically credible or not.

In the study reported here, we use four farm-scale models to quantify GHG emissions, using eight scenarios of dairy cattle production that reflect the climates, soils and feeding systems of dairy cattle farms in two contrasting milk-producing areas of Europe. The aim was to quantify the variation between models in emissions from on-farm sources and to assess the process of identifying the differences in the structure and function of the models giving rise to such variations.

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). An overview of the models is given in Table 1, with additional details in the Supplementary Material. Some models could simulate off-farm GHG emissions, such as pre- or post-farm emissions, and/or emissions associated with the use of farm machinery. However, these emission sources are not part of the agricultural emissions in the ESR, so were omitted from the comparison. Changes in the carbon (C) sequestered in the soil are part of the ESR but since this could not be simulated by all models, it was also omitted from the comparison. Steady-state simulations with no change in the C sequestered were used for those models that included this aspect. 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).

Table 1 here

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 (Eindhoven, The Netherlands; ‘Cool’) and warm with high rainfall (Santander, Spain; ‘Warm’). 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. 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 participants agreed a set of farm structure and management characteristics and parameters (Table 2). The GHG emissions 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, we chose to simulate a production system with a moderate production of 7000 kg ECM cow^{-1} year^{-1}.

Table 2 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. The corresponding analysis for differences between scenarios was determined using the anova function of the R programming language. Differences were considered significant if $p<0.05$ or less.

Results

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 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 median milk production values ranged from 10360 litres ha^{-1} for DairyWise to 8835 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. 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

Total GHG emissions expressed on an area basis (‘area emission intensity’; kg CO_2e ha^{-1} year^{-1}) were highest in DairyWise (Fig. 2A), significantly higher in relation to HolosNor and SFARMMOD, with the range between models equivalent to 18% of the mean of models. This mainly reflects the significantly higher number of livestock predicted by DairyWise, as can be seen by expressing emissions on the basis of a unit mass of milk (‘milk emission intensity’; kg CO_2e (kg ECM)$^{-1}$); the range between models is reduced to 6% of the mean of models, although there were still significant differences between models (Fig 2B). To prevent variations in livestock number from masking other differences between the models, the emissions from the on-farm sources will here be expressed as milk intensities rather than area intensities. Note that no allocation method was used when calculating the milk intensities (see Supplementary Material).

Figure 2 here

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 compared to FarmAC (Fig. 3C). Manure N_2O emissions (Fig. 3D) estimated by HolosNor were higher than those of the other models, significantly so compared to DairyWise and SFARMMOD.

Figures 3 here

There were significant differences between models for the N_2O emissions from both NH_3 volatilisation and NO_3^- leaching (Fig. 4). The emissions estimated by HolosNor were higher than by the other models, significantly so in some instances. For FarmAC, the emissions resulting from NO_3^- leaching were particularly variable between scenarios. The variation in GHG emissions from different sources between models is shown in Table 3. For each source, the mean of the emissions for the four models is subtracted from the emission for the individual model. The differences between models led to differences in the ranking of scenarios. DairyWise ranked the Cool climate higher than the Warm climate and thereafter grass only higher than grass/maize. FarmAC, HolosNor and SFARMMOD ranked grass only higher than grass/maize but there were no clear rankings for climate and soil.

Figure 4 and Table 3 here

Differences between scenarios

The production characteristics, and area and milk intensities for the different scenarios, averaged across models, are shown in Table 4. There were statistically significant differences between the feeding systems, with the grass only system requiring more concentrate feed (1.75 versus 1.13 Mg dry matter cow^{-1} year^{-1}), carrying a higher number of cows (69.3 versus 64.2 head) and receiving more N fertiliser (242 versus 232 kg N ha^{-1} year^{-1}). Significantly more N fertiliser was applied under the Warm climate than under the Cool (246 versus 228 kg ha^{-1} year^{-1}). The area emission intensity was around 11% greater for the grass only system than for the grass/maize (11.1 kg versus 10.0 kg CO_2e ha^{-1} year^{-1}). When expressed as milk emission intensities (kg CO_2e (kg ECM)$^{-1}$), the emissions under the Cool climate were significantly greater than under the Warm climate for enteric CH_4 (0.673 versus 0.669), manure CH_4 (0.259 versus 0.251), manure N_2O (0.025 versus 0.017) and the indirect N_2O emission resulting from NH_3 volatilisation (0.030 versus 0.028). The emissions for the Grass only were significantly greater than for the Grass/maize for enteric CH_4 (0.677 versus 0.666), soil N_2O (0.264 versus 0.247), manure CH_4 (0.128 versus 0.124), manure N_2O (0.022 versus 0.020), and the indirect N_2O emission resulting from NH_3 volatilisation (0.030 versus 0.028). The indirect N_2O emission from NO_3^- leaching was significantly higher for sandy soil than clay soil (0.028 versus 0.020). At the farm scale, the milk intensities were significantly higher for Grass only than for Grass/maize (1.119 versus 1.084) and for the Cool climate than for the Warm (1.127 versus 1.076). Across scenarios, enteric CH_4 and field N_2O emissions were the major contributors to total GHG emissions.

Table 4 here

Discussion

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 was due partly to a higher efficiency of the use of feed for milk production; 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 energy:protein ratio 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, corresponding 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

The scenario-averaged area emission intensity was highest for DairyWise (Fig. 2A). This was mainly due to the higher number of livestock that this model predicted could be supported on the farms, as the differences between models decrease when emissions are expressed as milk 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 feed quality is predicted by DairyWise, it could not be standardised here, meaning there were differences between models in the feed quality. Finally, there were differences in methods used to model enteric CH_4 emissions, which varied from a national Tier 3 method with 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 total input of plant-available N (manure plus fertiliser) was prescribed here so the crop production was largely decoupled from the behaviour of the livestock and manure management modules. However, 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 methodologies used (particularly emission factors) and in 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 manure DM content was assumed and in SFARMMOD, a constant factor independent of manure DM.

The low indirect emissions of N_2O associated with NO_3^- leaching predicted by DairyWise (Fig. 4B) is because it simulated a large N loss through 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 higher drainage.

The total GHG emissions 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, Alemu *et al.*, 2017). 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). In contrast, the differences between the ranking of scenarios between models shows that there can be systematic variations in the responses to climate and farm management.

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 milk emission intensities, relative to the model returning the lowest estimate, was 4-9% for the cold climate and 13-16% for the Warm climate.

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.

Effect of scenarios

More concentrate feed was required to provide a balanced diet in the grass only system than the grass/maize system (Table 4). 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 and the area emission intensity was higher. 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. Expressed in terms of milk emission intensities, manure CH_4 and N_2O emissions (direct and from NH_3 volatilisation) were lower under the Warm climate, due to the shorter housing period and therefore lower annual manure production. We have no immediate explanation for the higher enteric CH_4 emission under the Cool climate but note that is a small effect (1% difference). The higher emissions from enteric fermentation, manure and soil under the Grass versus the Grass/maize system may reflect a lower ability to construct a balanced feed ration with grass as the only roughage feed and therefore a lower efficiency of utilisation of feed for milk production in the former. This would increase the flow of DM and N through the livestock and manure management, per unit mass of milk produced. The N_2O emissions associated with NO_3^- leaching were greater for the sandy than clayey soil, due to the higher drainage. The lower farm-scale milk emission intensity in the Warm climate compared to the Cool mainly reflected the lower emissions associated with manure management (79% of difference) whereas the difference between the Grass and Grass/maize systems was mainly associated with the soil N_2O emission (47%). The total model-averaged area emission intensities calculated here are within the range 9.6 – 11.8 kg CO_2e ha^{-1} year^{-1} found for Ireland by O'Brien *et al.* (2011), similar to the 11.0 and 9.5 kg CO_2e ha^{-1} year^{-1} found for a farm in the USA by Veltman *et al.* (2017), lower than the 12.1 kg CO_2e ha^{-1} year^{-1} found for New Zealand by Beukes *et al.* (2011) but higher than that calculated using the relationship with milk production per unit area found by Christie *et al.* (2011) (adjusted to remove non-ESR emissions). However, as noted by Christie *et al.* (2011), comparing the results of different studies is difficult, due to variations in the methods used, so we here draw no other conclusion than that the results are within the range found in other studies and that the scenarios we chose were indeed an adequate basis for investigating the process of comparing the models.

Comparing GHG emissions from dairy cattle farm models

The advantage of using farm-scale models of dairy cattle production in the context of the ESR, particularly in relation to their ability to predict the consequences of mitigation measures on emissions and production, arises mainly because of their ability to account for the on-farm feedback processes. However, as we have shown here, the same feedback processes sometimes make it difficult to standardise all aspects of farm-scale scenarios and complicate the process of understanding the reasons for differences between model results. The maximum difference between models in area emission intensity was equivalent to about 18% of the mean of all models, equivalent to about half the average ESR reduction demand. The magnitude of this variation underscores the importance of understanding and assessing the credibility of farm models when they are used as part of national GHG emission accounting, and in gaining acceptance by producers, where a Member State choses to introduce GHG accounting at the farm scale. We believe this justifies further investment in methodologies and tools to support the comparison of farm-scale models. That investment needs to include the development of a wider range of scenarios, designed to encompass all European dairy production, and software tools to compare, analyse and present the large amount of data generated.

Conclusions

Based on the four farm-scale models used here, we conclude that there can be important differences between models in the GHG emissions predicted at the source and farm scales. These variations between models arise because of differences in the simulation of the processes and feedback loops driving production and emission, and the extent to which management functions are internalised. These model features complicate the standardisation of farm characteristics and management in scenarios and the interpretation of results. Nevertheless, we conclude that comparing the results of applying farm-scale models to a wide range of scenarios is a useful process for quality assurance and review, and that further investment in the development of scenarios and software tools is justified.

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Table 1 Overview of the methods used by the models to calculate key farm characteristics and emissions.

Category	Methods used by models*			
	DairyWise	*FarmAC*	*HolosNor*	*SFARMMOD*
Feed ration formulation	Optimized	Input	Optimized	Optimized
Milk production determination	Energy and protein	Energy and protein	Input	Optimized
Proportion of area for silage maize	Fixed (20%)	Input	Input	Optimized
Crop production	Tier 3	Tier 3	Input	Optimized
Enteric CH_4	Tier 3	Tier 2	Tier 2	Tier 2
Manure CH_4	Tier 2	Tier 2	Tier 2	Tier 2
Manure N_2O	Tier 2	Tier 2	Tier 2	Tier 3
Field N_2O	Tier 2	Tier 3	Tier 3	Tier 3
NH_3 emissions	Tier 3	Tier 3	Tier 2	Tier 3
NO_3^- leaching	Tier 3	Tier 3	Tier 2	Tier 3

***** See Supplementary Material

****** Tier 2 = Tier 2, IPCC (2006)**;** Tier 3 = modified Tier 2 and/or dynamic modelling

Table 2. Standardised farm data

Category	Standardised farm data
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
Beef cows	No beef calves or bulls
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 (unlimited by availability of nutrients or water)	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 3. Variation between models in the direct and indirect GHG emissions, relative to the mean of all models.

Model	Enteric CH_4	Soil N_2O	Manure CH_4	Manure N_2O	Indirect	Direct + indirect
	Deviation of individual model from mean of all models 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

* No allocation method used to partition emissions between milk and meat production (see Supplementary material)

Table 4 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 ha^{-1} $year^{-1}$							
Area emission intensity	11.4	9.9	11.2	10.0	11.2	9.9	10.8	10.0
	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	0.26	0.25	0.27	0.26	0.26	0.24	0.27	0.24
	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							
Milk emission 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.

** No allocation method used to partition emissions between milk and meat production (see Supplementary material)

Figure captions

Figure 1

Predicted 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 of the eight dairy farming scenarios. Differences between model results are not significantly different from one another if they share the same letter.

Figure 2

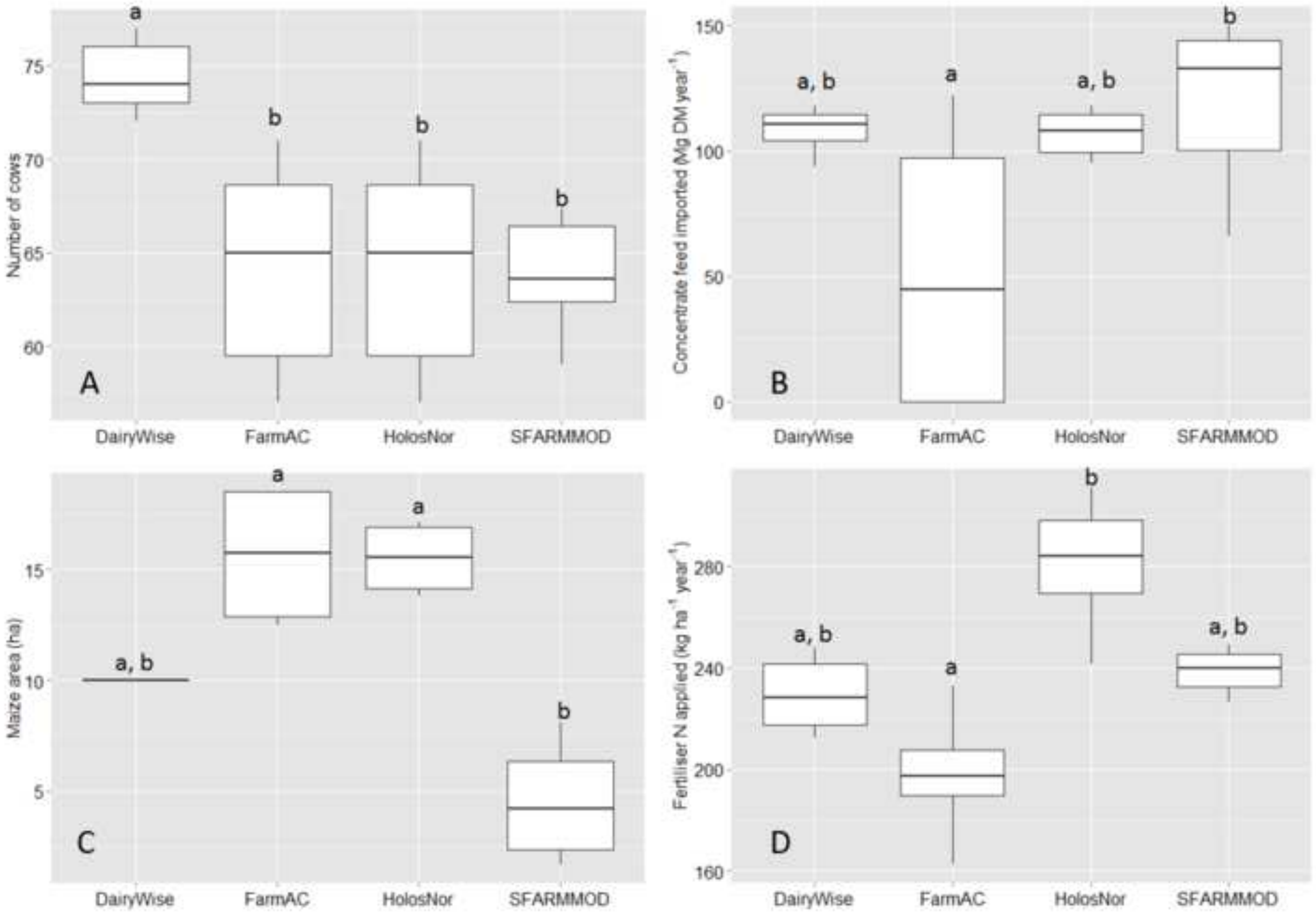
Total GHG emissions from all sources, expressed as an area emission intensity (kg CO_2e ha^{-1} year^{-1}) (A) and as a milk emission intensity (kg CO_2e (kg ECM)$^{-1}$) (B). The boxplots show the data median and quartiles. Differences between models are not significantly different from one another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

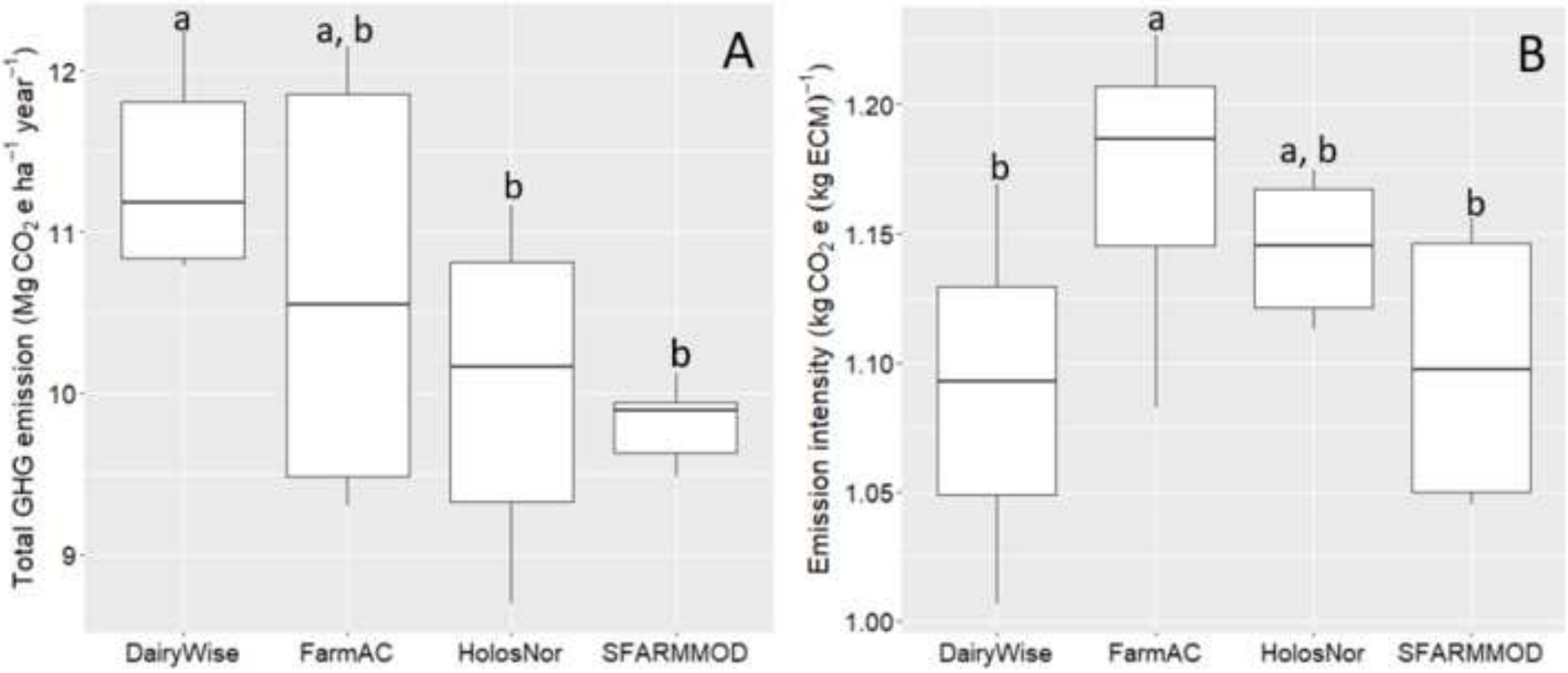
Figure 3

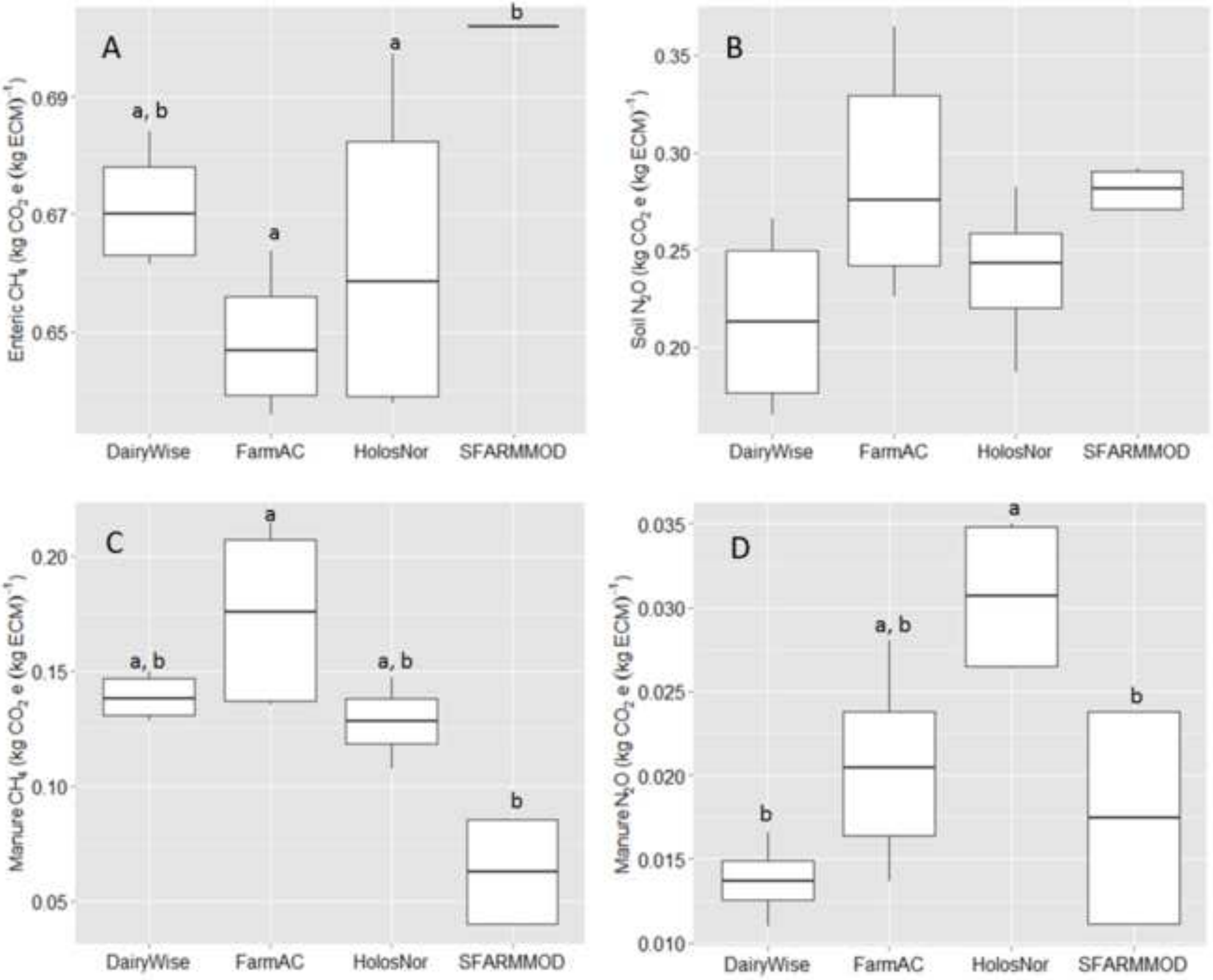
Direct GHG emissions; enteric CH_4 emissions (A), soil N_2O emissions (B), manure CH_4 (C) and manure N_2O emissions (D) (kg CO_2e (kg ECM)$^{-1}$). The boxplots show the data median and quartiles. Differences between models are not significantly different from one another if they share the same letter.

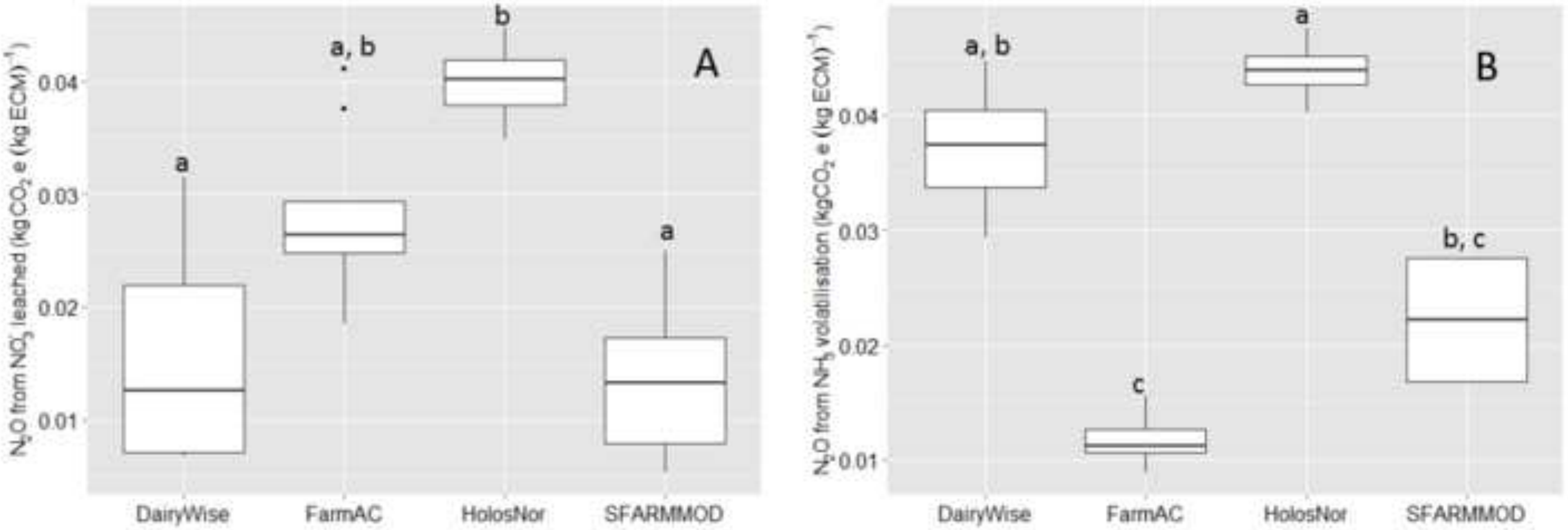
Figure 4

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.


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


A
Total GHG emission (Mg CO2 e ha-1 year-1)
12
11
10
9
a
a, b
b
b
DairyWise
FarmAC
HolosNor
SFARMMOD
B
Emission intensity (kg CO2 e (kg ECM)-1)
1.20
1.15
1.10
1.05
1.00
b
a
a, b
b
DairyWise
FarmAC
HolosNor
SFARMMOD


A
Enteric CH_4 (kg CO_2 e (kg ECM)$^{-1}$)
0.69
0.67
0.65
a, b
a
a
b
DairyWise
FarmAC
HolosNor
SFARMMOD
B
Soil N_2O (kg CO_2 e (kg ECM)$^{-1}$)
0.35
0.30
0.25
0.20
DairyWise
FarmAC
HolosNor
SFARMMOD
C
Manure CH_4 (kg CO_2 e (kg ECM)$^{-1}$)
0.20
0.15
0.10
0.05
a, b
a
a, b
b
DairyWise
FarmAC
HolosNor
SFARMMOD
D
Manure N_2O (kg CO_2 e (kg ECM)$^{-1}$)
0.035
0.030
0.025
0.020
0.015
0.010
b
a, b
a
b
DairyWise
FarmAC
HolosNor
SFARMMOD


A
B
N₂O from NO₃⁻ leached (kgCO₂ e (kg ECM)⁻¹)
N₂O from NH₃ volatilisation (kgCO₂ e (kg ECM)⁻¹)
0.01
0.02
0.03
0.04
a
a, b
b
a
a, b
c
a
b, c
DairyWise
FarmAC
HolosNor
SFARMMOD

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

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Models used

The order of the models is alphabetical, with no intention to rank them.

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 (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions are calculated in the sub-model greenhouse gas (GHG) emissions, which uses the emission factors from the Dutch emission inventories (Schils *et al.*, 2006). Methane emissions from enteric fermentation are calculated with the Tier 3 model developed by,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). Direct N_2O emissions are related to manure management, nitrogen (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 nitrate (NO_3^-) resulting from the oxidation of reduced N forms are calculated based on ammonia (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 emissions associated with the modelled NH_3 volatilisation 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.*, 2013) 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.* (2013) 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 GHG 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.*, 2013). The amount of concentrates required was calculated using a regression model (Åby *et al*., 2015) 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). Feed is calculated by a linear programme feed ration using dry matter, energy and protein with a 2-week timestep and annual steady state. The model optimises farm cropping which includes grass (grazing and silage) and forage maize silage for the livestock feed. Concentrates with differing energy and protein contents are available to supplement the differing forages.

Product-based emission intensity and allocation methods

The focus of the current work was the extent to which model intercomparison could contribute to quality control of estimates of GHG emissions used in connection with the ESR. The use of emission intensities expressed in kg CO_2e (kg ECM)$^{-1}$ in the main text of the paper was a device to remove the effect of differences between models in the efficiency of production at the animal level, so that other differences could be identified and investigated. However, we recognise that interest by commercial companies (Tesco PLC, 2016) and by those wishing to gain a holistic overview of the environmental impact of product mean that there may be some readers who are interested in the product-base emission intensities *per se*.

The calculation of product-based GHG emission intensities is commonly estimated using Life Cycle Analysis. Such analyses include pre- and post-farm GHG emissions. These were not included in the current study and nor were any on-farm emissions not included in the ESR. Since C sequestration in the soil could not be simulated by all the models in the study, this was excluded from the comparison (models that could simulate C sequestration were run to steady state, so there was no net change in the C sequestered in the soil).

When focussing on the product-based GHG emissions, it is common in systems in which there is more than one product to use one or more allocation methods to partition the environmental impact between products (e.g. Casey and Holden, 2005). In the scenarios presented in the main text, there are two products; milk and meat. The choice of allocation method can have a considerable effect on the resulting emission intensity (Rice *et al.*, 2017). No allocation method was employed when calculating the values reported in the main text of this paper. This is equivalent to following FAO (2010) and considering the production of calves for female replacement as an essential feature of the milk production system. Since male calves are exported at birth, the remaining meat production is minimal. Alternatively, using protein production as an allocation criterion, the GHG emissions would be partitioned 82% to milk and 18% to meat production.

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