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

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**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.

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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 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\(_2\)e (kg ECM\(^{-1}\)), was similar to the difference between the scenarios with the lowest and highest emission intensities (0.09 kg CO\(_2\)e (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.
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 (CO₂e) 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 (CH₄) from enteric fermentation and manure management and nitrous oxide (N₂O) from manure management and the soil. In addition, there are indirect GHG emissions in the form of N₂O, 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 SFARMMOD 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\(_2\)e year\(^{-1}\) and CO\(_2\)e (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\(_2\)O 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\(^{-1}\).
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$_2$O emission tended to be lower in the warm climate. The field N$_2$O 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$_2$e (kg ECM)$^{-1}$) than for the grass/maize (1.07 kg CO$_2$e (kg ECM)$^{-1}$), and greater for the cool climate (1.12 kg CO$_2$e (kg ECM)$^{-1}$) than the warm (1.07 kg CO$_2$e (kg ECM)$^{-1}$). The range of emission intensities (direct + indirect) was 0.09 kg CO$_2$e (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 HolosNor. 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\(_2\)e (kg ECM\(^{-1}\)) respectively. Across scenarios, the range of emission intensities was greatest for DairyWise (0.16 kg CO\(_2\)e (kg ECM\(^{-1}\)) and least for HolosNor (0.06 kg CO\(_2\)e (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.

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$_2$O 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$_2$O 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.

Indirect N$_2$O emissions resulting from NH$_3$ volatilisation and NO$_3^-$ leaching (kg CO$_2$e (kg ECM)$^{-1}$) are shown in Fig. 4. There were large and significant differences between models for the N$_2$O 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$_2$e (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 warm 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$_2$O 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$_2$O emissions according to temperature. The direct N$_2$O 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$_2$O 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\textsubscript{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\textsuperscript{2} (kg ECM\textsuperscript{-1}
for the cool and warm climates respectively). In contrast, the values were lower than
the 1.2 kg CO\textsubscript{2e} (kg ECM\textsuperscript{-1} found for Portuguese dairy farms by Pereira and
Trindade (2015) and higher than the 0.83 and 0.73 kg CO\textsubscript{2e} (kg ECM\textsuperscript{-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\textsubscript{4} and N\textsubscript{2}O found here
(mean of 0.67 and 0.26 kg CO\textsubscript{2e} (kg ECM\textsuperscript{-1} respectively) were, however, higher
than those found by Gerber et al. (2011) (0.54 and 0.24 kg CO\textsubscript{2e} (kg ECM\textsuperscript{-1}
respectively, after adjusting to the GWP for CH\textsubscript{4} and N\textsubscript{2}O 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$_2$O 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$_2$O 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 CH₄ was the major source, followed by soil N₂O 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 CH₄ > indirect emissions > manure N₂O. 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 N₂O 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 CH4 and soil N2O 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 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. 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.

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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 Systems 147, 24-37.


<table>
<thead>
<tr>
<th>Category</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy cows</td>
<td>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*</td>
</tr>
<tr>
<td>Young animals</td>
<td>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</td>
</tr>
<tr>
<td>Manure management</td>
<td>Livestock housing; freely-ventilated, fully slatted floor, manure storage; slurry tank with natural crust, manure application; broadcast spreader, no incorporation</td>
</tr>
<tr>
<td>Fields</td>
<td>Total area; 50 ha, irrigation; none</td>
</tr>
<tr>
<td>Crop potential DM yield (with irrigation if necessary)</td>
<td>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.</td>
</tr>
<tr>
<td>N fertilisation</td>
<td>Grass; 275 kg plant-available N ha⁻¹ year⁻¹. Maize 150 kg plant-available N ha⁻¹ year⁻¹ **</td>
</tr>
</tbody>
</table>

* 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

<table>
<thead>
<tr>
<th>Scenario*</th>
<th>CSG</th>
<th>CSM</th>
<th>CCG</th>
<th>CCM</th>
<th>WSG</th>
<th>WSM</th>
<th>WCG</th>
<th>WCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dairy cows head</td>
<td>69</td>
<td>62</td>
<td>69</td>
<td>63</td>
<td>70</td>
<td>65</td>
<td>69</td>
<td>67</td>
</tr>
<tr>
<td>Imported concentrate feed</td>
<td>126</td>
<td>67</td>
<td>124</td>
<td>82</td>
<td>116</td>
<td>67</td>
<td>116</td>
<td>78</td>
</tr>
<tr>
<td>Maize area</td>
<td>0</td>
<td>13</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Fertiliser N</td>
<td>231</td>
<td>221</td>
<td>232</td>
<td>228</td>
<td>252</td>
<td>238</td>
<td>253</td>
<td>240</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>kg CO₂e (kg ECM)^⁻¹</th>
<th>Direct emissions</th>
<th>Indirect emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enteric CH₄</td>
<td>0.68</td>
<td>0.67</td>
</tr>
<tr>
<td>Manure CH₄</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Manure N₂O</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Field N₂O</td>
<td>0.27</td>
<td>0.25</td>
</tr>
<tr>
<td>Volatilization of NH₃</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Leaching of NO₃⁻</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Total emissions</td>
<td>1.17</td>
<td>1.14</td>
</tr>
</tbody>
</table>

* 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.

<table>
<thead>
<tr>
<th>Model</th>
<th>Enteric CH₄</th>
<th>Soil N₂O</th>
<th>Manure CH₄</th>
<th>Manure N₂O</th>
<th>Indirect</th>
<th>Direct + indirect</th>
</tr>
</thead>
<tbody>
<tr>
<td>DairyWise</td>
<td>0</td>
<td>-42</td>
<td>13</td>
<td>-7</td>
<td>0</td>
<td>-36</td>
</tr>
<tr>
<td>FarmAC</td>
<td>-23</td>
<td>33</td>
<td>48</td>
<td>0</td>
<td>-13</td>
<td>44</td>
</tr>
<tr>
<td>HolosNor</td>
<td>-8</td>
<td>-16</td>
<td>2</td>
<td>10</td>
<td>31</td>
<td>19</td>
</tr>
<tr>
<td>SFARMMOD</td>
<td>31</td>
<td>26</td>
<td>-63</td>
<td>-3</td>
<td>-17</td>
<td>-27</td>
</tr>
<tr>
<td>Mean of models</td>
<td>670</td>
<td>260</td>
<td>130</td>
<td>20</td>
<td>50</td>
<td>1130</td>
</tr>
</tbody>
</table>
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\(_2\)e year\(^{-1}\)) (A) and as an emission intensity (kg CO\(_2\)e (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\(_2\)O emissions (B), manure CH\(_4\) (C) and manure N\(_2\)O emissions (D) (kg CO\(_2\)e (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\(_2\)O emissions resulting from leaching of NO\(_3^-\) (A) and from volatilisation of NH\(_3\) from manure management and field-applied manure (B) (kg CO\(_2\)e (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.
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, N₂O, and CO₂ 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 CH₄ 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 N₂O 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 N₂O emissions resulting from the partial denitrification of NO₃⁻ 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 (CO₂ and NH₃), manure storage (CO₂, CH₄, N₂O, N₂ and NH₃) and for N₂O, N₂ and NH₃ 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 N₂O emission associated with the modelled NH₃ volatilisation and NO₃⁻ 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 CH₄ emissions from enteric fermentation and manure, direct N₂O emissions from agricultural soils, indirect N₂O emissions resulting from NO₃⁻ leached, N in run-off and NH₃ volatilised. Both direct and indirect N₂O 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$_2$e 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$_2$O
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

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