Comparison of process-based models to quantify major nutrient flows and greenhouse gas emissions of milk production

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ABSTRACT

Assessing and improving the sustainability of dairy production systems requires an accurate quantification of greenhouse gas (GHG) emissions and major nutrient (N, C, P) flows associated with milk production at the animal, farm and field-scale. Life cycle inventory databases are, however, often based on rough estimates of GHG emissions and nutrient flows, and cannot account for spatially-explicit variation in these flows. Emission estimates can be improved when underlying processes influencing GHG emissions and nutrient balances are explicitly considered. We aim to improve life cycle inventory databases for milk production in the US by integrating process-based models into LCA data acquisition. We therefore perform a quantitative comparison of five process-based models to determine major nutrient flows and GHG emissions of milk production at the animal, farm and field-scale.

Keywords: milk production, nutrient flows, greenhouse gas (GHG) emissions, process-based models

1. Introduction

The livestock production sector is a key contributor to a range of critical environmental problems, at local, regional and global scales (Steiner et al. 2006, Pelletier and Tyedmers, 2010, Bouwman et al. 2013). Ruminant livestock systems contribute substantially to global warming through greenhouse gas (GHG) emissions. The global dairy sector is presently responsible for 2.7% of total, global greenhouse gas emissions (FAO, 2010). In the US, the agricultural sector is responsible for 8.1% of total GHG emissions (EPA, 2014). After fossil fuel, enteric and manure methane (CH_4) emissions are the second and third most important sources of GHG from the dairy supply chain in the US (Thoma et al. 2013). In addition, crop-livestock production systems are the largest cause of human alteration of the global nitrogen (N) and phosphorus (P) cycles (Bouwman et al. 2013). Total N and P in animal manure exceed global N and P fertilizer use (Bouwman et al. 2013) and livestock manure is a major source of anthropogenic ammonia (NH_3) emission in the U.S. (NRC, 2003) and globally (Steiner et al. 2006).

Assessing and improving the sustainability of dairy production systems thus requires an accurate quantification of greenhouse gas (GHG) emissions and major nutrient (N, C, P) flows associated with milk production at the animal, farm and field-scale. In large, nonhomogeneous countries like the US, milk production practices and climate conditions vary widely, which can result in large, farm-specific variations in GHG and nutrient emissions (Henderson et al. 2013). Life cycle inventory databases are, however, often based on rough estimates of GHG emissions and nutrient flows, and cannot account for spatially-explicit variation in these flows. Emission estimates can be improved when underlying processes influencing GHG emissions and nutrient balances are explicitly considered (e.g. Schils et al. 2004, Li et al. 2012). We aim to improve life cycle inventory databases for milk production by integrating process-based models into LCA data acquisition. We therefore perform a quantitative comparison of five process-based models to determine major nutrient flows and GHG emissions of milk production at the animal, farm and field-scale. We compare these models in terms of GHG and NH_3 emissions to air, as well as nitrate (NO_3^-) and phosphate (PO_4^{3-}) emissions to ground water, and allocate these emissions to the different dairy production components, including five feed crops, animal (enteric) emissions, and manure management. This model comparison study is part of a larger project that aims to reduce the life cycle environmental impact of dairy production systems in the USA (www.sustainabledairy.org). Here, we present the results of the first round of model comparison, which focussed on GHG and NH_3 emissions to air.

2. Methods

2.1. Model description

In the model comparison, we included five process-based models: CNCPS6.1, DAYCENT, ManureDNDC, APEX and IFSM3.4 (Table 1). These models operate on different scales, each having their own unique features. The *Cornell Net Carbohydrate and Protein System (CNCPSv6.1*) model is an animal scale model that predicts changes in N_2O, CH_4, and NH_3 emissions for a wide range of feed, environmental and ration characteristics (Tylutki et al. 2008). The model provides enteric emissions and nutrient balances per cow.

Table 1. Included process-based models

Model	Scale	Reference
CNCPSv.6.1	Animal	www.cncps.cornell.edu/
DAYCENT	Field	www.nrel.colostate.edu/
DNDC-manure	Farm	www.dndc.sr.unh.edu/
APEX	Field to watershed	www.epicapex.tamu.edu/
IFSM	Farm	www.ars.usda.gov/

DAYCENT is a daily-time step, plant-centric soil biogeochemical model (Del Grosso et al. 2001, 2002, 2005). Model outputs include daily fluxes of various N-gas species (e.g., N_2O, NO_x, N_2), daily CO_2 flux from heterotrophic soil respiration, soil organic C and N, net primary productivity (NPP), daily water and nitrate (NO_3) leaching, and other ecosystem parameters. *Manure-DNDC* provides a detailed description of the on-farm biochemical cycle of N and P as well as the use of water for each individual crop (alfalfa, corn, grass, soybean and wheat). The model can be used for predicting crop growth, soil temperature and moisture regimes, soil carbon dynamics, nitrogen leaching, and emissions of trace gases including nitrous oxide (N_2O), nitric oxide (NO), dinitrogen (N_2), ammonia (NH_3), methane (CH_4) and carbon dioxide (CO_2). A specific feature of DNDC is the biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems (Li et al. 2012). *APEX* (Williams et al. 2012) is a comprehensive daily-time step model able to link field to watershed-scale, simulating detailed agricultural management and quantifying productivity as well as impacts on a suite of environmental processes (hydrology, erosion, net ecosystem exchange, soil carbon dynamics, nitrogen balance, etc.) (Gassman et al., 2010). The model can be configured to simulate pertinent management strategies, such as rotational grazing, movement of animals between paddocks, and application of manure removed from livestock feedlots or waste storage ponds. *The Integrated Farm System Model (IFSM)* provides a process level simulation of farm production systems and predicts the performance, economics, and environmental impacts of alternative production practices (Rotz et al., 2012). IFSM provides field scale emissions for individual crops, use of machinery, enteric emission, manure management and other flows from the barn.

2.2 Model comparison – whole farm approach

For model comparison, the whole-farm model approach was used, which is an established powerful methodology to develop GHG mitigation strategies for farming systems (e.g., Schils et al. 2005, Schils et al. 2007, del Prado et al. 2013). The whole-farm approach reveals trade-offs between emissions of the different GHGs and other pollutants, and ensures that interactions between nutrient cycles are taken into account (Schils et al. 2005). All models were run for a dairy farm in New York state, using the same input data. Emissions of NH_3 and important greenhouse gases, e.g. CH_4 and N_2O, were collected for each model. As not all models include the same processes, emissions were allocated to three main farm processes, e.g. barn, manure handling, and field, to facilitate a meaningful comparison of the models. Barn emissions were further segregated into “enteric emissions from livestock” and “other barn emissions”, such as ground emissions. “Field” emissions include all emissions associated with crops and soil, such as soil N_2O emissions.

Total global warming impacts were quantified for each farm process by multiplying the emissions of CH_4 and N_2O with the substance-specific global warming potential (GWP100, IPCC 2007, 1 for CO_2, 25 kg_{CO2eq}/kg_{CH4} and 298 kg_{CO2eq}/kg_{N2O}). These substance-specific global warming impacts can be aggregated to obtain the total global warming impact (in CO_2 equivalents). At this stage, biogenic CO_2 emissions were excluded from the quantification of global warming impacts, assuming that the total biogenic CO_2 input balances the biogenic CO_2 output.

2.3 Pilot farm

Input data collected for the NY state farm, include detailed feed scenarios, use of machinery on the farm, a description of feed crop cultivation practices and a description of the manure management system. A summary of the main farm characteristics is provided in Table 2.

Table 2. Summary of farm characteristics

Dairy cows (number)	Annual average production (lbs/head)	Housing	Manure management	Crop types	On-farm feed production
1100 lactating 165 dry cows 425 older heifers 500 young heifers	26364	Free stall	Slurry with natural crust	485.6 ha corn 344 ha alfalfa 48.6 ha soybean 80.9 ha small grain 60.7 ha grazing	85%

3. Results

3.1 GHG emissions

First results show that predicted enteric CH_4 emissions dominate GHG impacts at the individual farm level (Fig. 1). Enteric CH_4 emissions, are similar for ManureDNDC v3, IFSM3.4 and CNCPS6.1 and range from $2.0\cdot10^5$ kgCH$_4$/yr to $2.4\cdot10^5$ kgCH$_4$/yr, leading to a dominant GHG contribution between $5.0\cdot10^6$ and $5.9\cdot10^6$ kgCO$_{2equ}$/yr. For the other farm processes, predictions of GHG emissions differ more between models. ManureDNDC and IFSM3.4 differ in their prediction of manure emissions (both CH_4 and N_2O) and barn N_2O emissions. IFSM3.4 predicts a relatively large contribution, i.e. ~20%, of manure CH_4 to total GHG impacts, whereas the contribution of manure CH_4 to total GHG impacts is only 3% in manureDNDC predictions. Alternatively, manureDNDC predicts a relatively large contribution of barn N_2O emissions to total GHG impacts (15%), whereas these emissions are not included in IFSM3.4. Particularly striking is the difference in predictions of field N_2O emissions. The DayCent prediction of $1.5\cdot10^4$ kgN$_2$O emitted per year is substantially higher than the predictions of ManureDNDC, IFSM3.4, which are $1.2\cdot10^3$ kgN$_2$O/yr and $1.7\cdot10^3$ kgN$_2$O/yr, respectively. APEX predicts an emission of $1.9\cdot10^3$ kgN$_2$O/yr (excluding fallow land), and an emission of $4.2\cdot10^3$ kgN$_2$O/yr if most of the manure is assumed to be applied on a fallow land. On a per crop basis, other differences between model field N_2O predictions appear (Fig. 2). Both APEX and DAYCENT predict a high contribution of alfalfa to total N_2O emissions, whereas alfalfa contributes only slightly to the total N_2O emissions from the field in manureDNDC predictions. ManureDNDC predicts a dominant contribution of corn (46%) to total N_2O emission. This is consistent with DAYCENT predictions, where corn, next to alfalfa, dominates total N_2O field emissions.

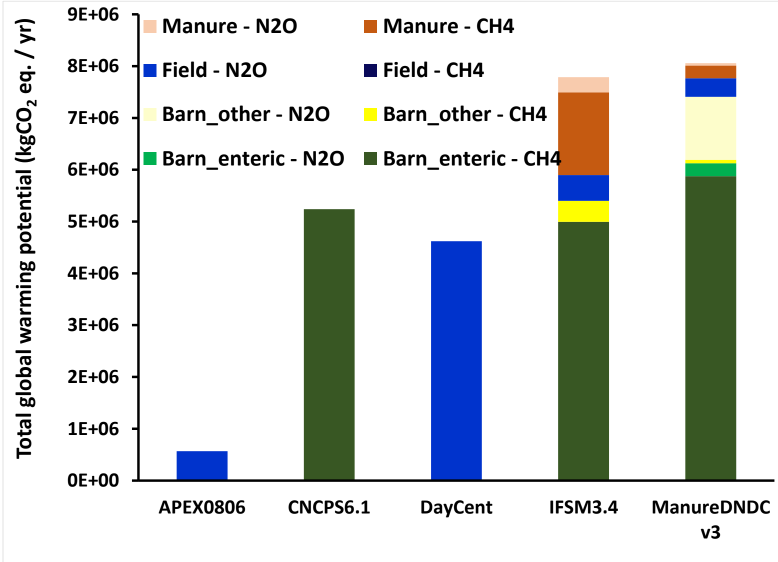

Figure 1. Comparison of total annual global warming impact calculated by five process models for field barn and manure management systems of the pilot NY farm

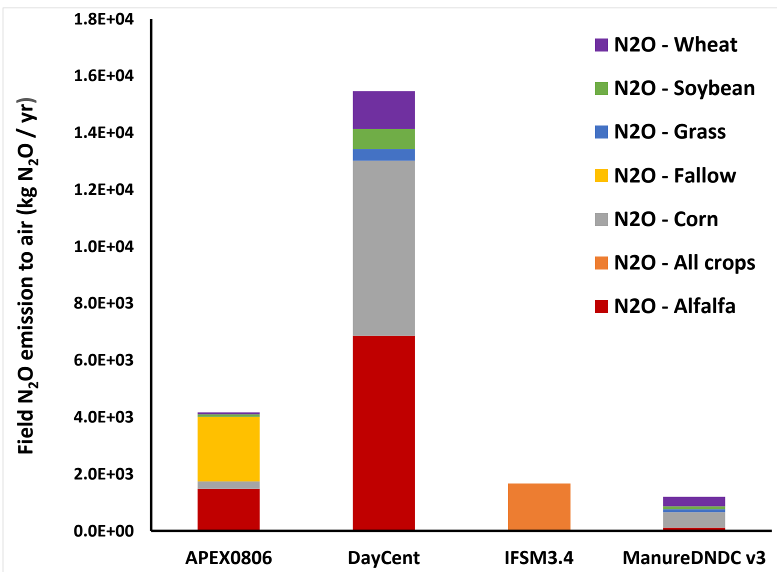

Figure 2. Crop-specific nitrous oxide (N_2O) emission to air for crop production calculated by four process models

3.2 Ammonia emission

This first model comparison show that predictions of ammonia emissions to air are mostly similar across models (Fig. 3). Predictions of barn NH_3 emissions are very close for ManureDNDC and CNCPS6.1, i.e. $4.3 \cdot 10^4$ kgNH_3/yr and $4.5 \cdot 10^4$ kgNH_3/yr, respectively. These emissions are a factor of 1.6 higher than the barn NH_3 emissions predicted by IFSM3.4. Field NH_3 emissions are highly comparable between ManureDNDC, IFSM3.4 and APEX, ranging from $1.4 \cdot 10^4$ kgNH_3/yr to $1.9 \cdot 10^4$ kgNH_3/yr. Manure NH_3 is highly comparable as well. Manure NH_3 emission estimations differ by a factor 1.1 between IFSM and ManureDNDC. CNCPS6.1 predicts only livestock emissions.

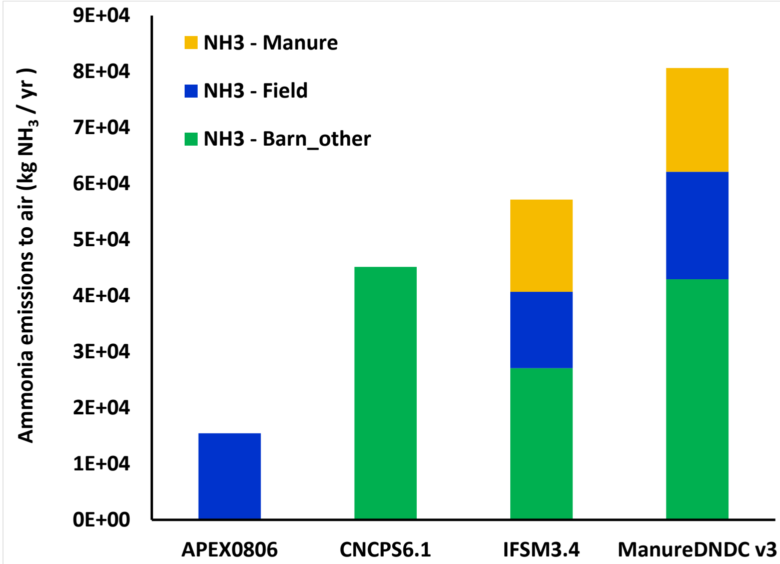

Figure 3. Ammonia emissions to air

4. Discussion

Results of the first round of model comparison show that enteric CH_4 emissions are dominating the total global warming impact at the individual farm level. This finding is consistent with results from other studies. Thoma et al. (2013) showed that enteric CH_4 emission contribute 25% of total C footprint of the dairy supply chain. In addition, DelPrado et al (2013) found that enteric CH_4 and crop land N_2O are the main contributors to whole-farm greenhouse gas impacts for grassland ruminant-based farms system in Europe, although large site- and farm-specific variations were observed.

The different models vary primarily in their prediction of N_2O emissions related to barn and field. One of the reasons for these differences can be that not all models were run with exactly the same input data. A closer inspection of model input data revealed that model input data differ in terms of meteorological data and soil type. Current research efforts focus on further harmonization of input data. A further analysis of model differences will be carried out after the second modelling round with the harmonized input data set. Model validation will then be carried out on another pilot farm for which more detailed experimental data are available. Finally, for improving the process modelling of N_2O flows, the monitoring tasks of the larger project will provide empirical measurements of field barn and manure emissions.

5. Conclusion

A first comparison of five process-based models shows that enteric CH_4 emissions are dominating the total global warming impact at the individual farm level. It is thus necessary to accurately predict and measure these enteric CH_4 emissions. Field CH_4 emissions play only a minor role in the total global warming impact of the individual farm. There may be less urgency to monitor variations in field CH_4 emissions. Model predictions mainly differ in terms of field N_2O emissions, which may partly result from differences in input variables. Current research focusses on further harmonization of the input data for the pilot farm, which will be used for the second model round. In this second round, we will extend the model comparison to nitrate (NO_3^-) and phosphate (PO_4^{3-}) emissions to groundwater. In addition, we will establish and compare whole-farm nutrient (C, N, P) balances. Once models are evaluated and harmonized, integrating process-based models into LCA data acquisition, as proposed here, can provide a more accurate, spatially-explicit approach to derive farm-specific nutrient flows and GHG emissions, which is essential to improve sustainability assessments of (US) dairy production systems.

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