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

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ABSTRACT

Assessing and improving the sustainability of dairy production systems is essential to secure future food production. This requires a holistic approach that reveals trade-offs between emissions of the different greenhouse gases (GHG) and nutrient-based pollutants and ensures that interactions between farm components are taken into account. Process-based models are essential to support whole-farm mass balance accounting, however, variation between process-based model results may be large and there is a need to compare and better understand the strengths and limitations of various models. Here, we use a whole-farm mass-balance approach to compare five process-based models in terms of major nutrient (N, P) flows and greenhouse gas (GHG) emissions associated with milk production at the animal, farm and field-scale. Results show that predicted whole-farm, global warming impacts were very similar for the two whole farm models with a predicted global warming impact of approximately $1.1\cdot10^7$ kg CO_2eq./year for both models and a dominant contribution of enteric CH_4 emissions. Model predictions were also highly comparable, i.e. within a factor of 1.5, for most nutrient flows related to the animal, barn and manure management system, including enteric CH_4 emissions, and NH_3 emissions from the barn. In contrast, predicted field emissions of N_2O and NH_3 to air, and N and P losses to the hydrosphere, were very variable across models. This indicates that there is a need to further our understanding of soil and crop nutrient flows and that measurement data on nutrient emissions are particularly needed for the field. In addition, there is a need to further understand how the anaerobic digester influences the manure composition and subsequent emissions of N_2O and NH_3 after application of the digestate to the field. Empirical data on manure composition before and after anaerobic digestion are essential for model evaluation. The whole-farm mass-balance approach is advocated as an essential tool to assess and improve the sustainability of dairy production systems. Our comparison of five process-based models provides insight into the range of expected emissions associated with milk production.

Keywords: whole-farm mass-balance; 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 environmental challenges, at local, regional and global scales (Steiner et al. 2006, Pelletier and Tyedmers, 2010, Bouwman et al. 2013). Ruminant livestock systems contribute to global warming through GHG emissions. The global dairy sector is reported to be responsible for 2.7% of total, global greenhouse gas emissions (FAO, 2010). In the US, the dairy sector is responsible for approximately 1.9% of US GHG emissions (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). This has resulted in large-scale anthropogenic disturbances in N and P cycles with repercussions for human health (e.g. secondary particle formation due to ammonia (NH_3) emission and drinking water contamination by nitrate (NO_3^-)) and the environment (e.g. eutrophication of lakes and coastal waters and exacerbation of hypoxic zones) (Schindler et al. 2008; Davidson et al. 2012). Finally, phosphorus is a limited resource and sustaining an adequate phosphorus supply has been identified as a major emerging challenge (Cordell and White, 2014).

Assessing and improving the sustainability of dairy production systems is essential to secure future food production. This is, however, challenging. First, 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 (Del Grosso et al. 2005; Henderson et al. 2013). Second, in dairy production systems, nitrogen (N), phosphorus (P) and carbon (C) flows are extremely intertwined. As a result, mitigation of one specific pollutant can result in an increase in emissions of other environmental pollutants. For example, a modelling study by Dijkstra et al. (2011) suggested that dietary strategies aimed at reducing N excretion from dairy cows may result in elevated methane (CH_4) emissions. Third, nutrient flows between farm components, such as the animal herd, the manure management system, the field, and the feed, are strongly linked. Altering one aspect of this nutrient cycle can have major effects on nutrient flows to or from other farm components.

Understanding trade-offs between emissions of the different GHGs and nutrient-based pollutants, ensures that interactions between nutrient and C cycles, and interactions between farm components are considered in management decisions. Commonly used sustainability assessment methodologies such as life cycle assessment (LCA) often employ Intergovernmental Panel on Climate Change (IPCC) emission factors to quantify emissions of GHGs and nutrient-based pollutants. These emission factors are often based on rough estimates of GHG emissions and nutrient flows and cannot account for temporal and spatially-explicit variations in these flows. In addition, emission factors do not consider nutrient cycling between different farm components and do not account for interaction between N, P, and C flows. From a sustainability perspective, this is problematic as it may result in masked nutrient imbalances, i.e. unaccounted losses or gains of nutrients at the animal, field or farm scale. It may also result in sub-optimal improvements when trade-offs occur, e.g. when strategies to reduce N excretions from dairy cows result in elevated CH_4 emission, as described above, or when an optimized nutrient use efficiency in one farm component negatively affects the nutrient use efficiency in other farm components. Finally, it is generally thought that the environmental performance of dairy farms can be improved by improving nutrient cycling efficiency between farm components, as an improved cycling efficiency would naturally result in lower nutrient losses, hence requiring a consideration of nutrient cycling between farm components.

The whole-farm approach is a holistic approach that explicitly considers nutrient cycling between farm components (e.g., Schils et al. 2005, Schils et al. 2007). The whole-farm approach includes a mass-balance analysis that considers nutrient imports to the farm and nutrient exports from the farm, as well as internal nutrient flows between farm components, including animal herd, barn, manure management system, field and feed. It is a 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). Parameterization of a whole-farm mass-balance is, however, challenging as it is difficult, relatively inaccurate, and very expensive to measure the assimilation and emission of GHGs on farms and to empirically determine whole-farm internal nutrient flows (Rotz et al., 2010). Process-based models can predict flows when empirical data are lacking (e.g. Del Grosso et al. 2005, Schils et al. 2005, Li et al. 2012). In addition, process-based models can account for underlying processes influencing GHG emissions and nutrient balances and they may yield more reliable results than emission factors (e.g. Del Grosso et al. 2005, Schils et al. 2005, Li et al. 2012). It is thus reasoned that the whole-farm approach may be particularly powerful when process-based models are used to predict emissions and internal nutrient flows simultaneously. Variation between process-based model results may, however, be large; thus, there is a need to compare and better understand the strengths and limitations of various models and to analyse the level of concordance between models to provide potential ranges in emissions flows and nutrient efficiencies. Currently, a comprehensive study analysing both nitrogen and phosphorus balances and efficiencies together with GHG and nutrient related emissions is lacking.

In response to these needs, we performed a quantitative comparison of five process-based models in a whole-farm mass-balance context. Specifically, we compared models in terms of whole-farm mass-balance flows, including internal N and P flows and GHG and nutrient-related emissions to the environment. The objectives of this research were: *i*) to compare process-based models in a whole-farm mass-balance context, that is in terms of predicted nutrient flows and GHG emissions, and *ii*) to analyse the level of concordance between the models and to identify needs for improvement. This model comparison study provides a basis for evaluating GHG mitigation and nutrient efficiency optimization strategies and 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). The output of the process-based models will in particular be used to inform sustainability assessment methodologies, such as LCA. A follow-up project will focus on (partial) model evaluation with field measurement data.

2. Methods

All models were used to simulate a commercial dairy farm in New York using harmonized input data. We first analysed the whole-farm N and P mass-balances, comparing the models to each other and to empirical data. Nutrient use efficiencies were calculated for the whole-farm and relevant farm components (feed, field) in order to assess the performance of the whole-farm, to compare overall nutrient use efficiencies and to identify key farm components in terms of nutrient loss. Subsequently, we compared the models in terms of NH_3, and N_2O emissions to air, N and P nutrient losses from soil to ground water, as well as global warming potentials.

2.1. Model descriptions

In the comparison, we included five process-based models: CNCPS6.1.54, DayCent4.5, ManureDNDC, APEX0806 and IFSM4.2. All included models are well-established and have been partially evaluated with empirical data for different farm components (e.g. *IFSM*: Rotz et al. 1999, Rotz et al. 2006, Rotz et al. 2014, *Manure-DNDC*: Deng et al. 2015, Li et al. 2012, Giltrap et al. 2010, *CNCPS*: Higgs et al. 2012, Higgs et al. 2013, *APEX*:

Gassman et al. 2010, *DayCent:* Jarecki et al. 2008, Del Grosso et al. 2008a). The models operate on different scales, each having their own unique features. The *Cornell Net Carbohydrate and Protein System (CNCPSv6.1* www.cncps.cornell.edu/) model is an animal scale model that predicts changes in N_2O and CH_4 emissions for a wide range of feed, environmental and ration characteristics (Tylutki et al. 2008, Van Amburgh et al. 2010, Higgs et al. 2012, Higgs et al. 2013). The model provides enteric emissions and nutrient balances per cow. *DayCent (*www.nrel.colostate.edu/) 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. *APEX* (Williams et al. 2012, www.epicapex.tamu.edu/) 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. *Manure-DNDC* (www.dndc.sr.unh.edu/) 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 and winter 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). *The Integrated Farm System Model (IFSM,* http://www.ars.usda.gov/Main/docs.htm?docid=8519/*)* provides a process level simulation of farm production systems that is used to predict the performance, economics, and environmental impacts of alternative production practices (Rotz et al., 2012). IFSM provides emissions for all major farm components including individual crops, machinery, cattle, and various manure sources. IFSM uses a range of methods to quantify emissions, including process simulation and process related empirical relationships and emission factors for simple processes.

2.2 Model comparison – whole farm nutrient balance and use efficiency

We used a whole-farm, mass-balance framework to compare the different models (Fig. 1). In our analysis, we distinguished six internal farm components, i.e. 'animal', 'barn', 'manure', 'soil', 'crop', and 'feed'. These farm components are linked in terms of nutrient flows. Nutrient outflows from the farm include emissions to the environment, such as enteric N_2O emissions, and export of products (milk, animals, cash crops and manure). Whole-farm nutrient imports are comprised of purchased feed, purchased and applied inorganic fertilizer (hereafter: 'fertilizer'), N fixation by leguminous crops, N fixation by soil, and N and P deposition. Nutrient imports and exports were allocated to the appropriate farm component and all mass-balance flows were expressed in kg nutrient (N or P) per year.

To ensure a uniform model comparison, we ran all models for a commercial dairy farm in New York State, using the same input database. For each model, we extracted all available nutrient flows that contribute to the whole-farm mass-balance (Fig. 1) in order to establish model-specific mass-balances. As models focus on different farm components, we obtained several partial mass-balances, i.e. an animal balance for CNCPS, field balances for DayCent and APEX, and whole-farm balances for IFSM and ManureDNDC. All models were run with historical weather data representative of the NY farm site. Weather data was obtained from the North American Regional Reanalysis (http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html) to provide daily maximum and minimum temperature, precipitation, wind speed, and relative humidity while solar radiation was estimated using APEX0806. The farm used an eight year crop rotation cycle and all models, except CNCPs, were therefore run for at least 8 years. ManureDNDC was adapted to accommodate an 8 year crop rotation cycle. Adaptations included an incorporation of 'carry-over' of manure from one year to the other in the lagoon and digester. IFSM simulations were run for 25 years and the average annual model output was used to obtain typical nutrient flows and carbon-based GHG emissions. For DayCent and APEX a 20 year (1980-1999) spin-up phase was used. Both models were run from 1980 to 2013 and model outputs from 2000 to 2013 were averaged to obtain typical nutrient flows and carbon-based GHG emissions.

The empirical data indicated an unrealistically large loss of N during manure storage. This was supported by IFSM simulations, i.e. IFSM predicted a higher manure N application rate to the field based on the number of cows on the farm. As a higher application of manure N on soil would lead to higher N emissions, we adjusted the 'empirical' manure application rates for the field models APEX and DayCent. That is, APEX and DayCent were run with IFSM predicted manure application rates assuming the same percentages of manure applied per crop as in the empirical data.

Field application of manure contributes substantially to whole-farm ammonia emissions. At present, DayCent does not simulate ammonia volatilization from manure application on the field, whereas this process is simulated in the other models. To ensure a uniform comparison, we subtracted the potential amount of N lost due to ammonia volatilization from the total amount of N in manure applied to the field in DayCent simulations. The potential amount of NH_3-N volatilized was obtained from IFSM simulations. Field ammonia emissions predicted by DayCent represent NH_3 volatilization of a plant-specific portion of harvested or senesced biomass N (del Grosso et al. 2008b).

Nutrient use efficiencies were calculated at three different levels of the dairy production chain, i.e. feed-, field- and the whole-farm-level. There are various definitions for nutrient use efficiency used in the literature (e.g. Oenema et al. 2009). Here, feed-NUE equals the nitrogen output via milk & meat divided by the total N intake from feed. Field-NUE equals the nitrogen output in harvested crops divided by the total nitrogen input into the field, i.e. sum of nitrogen applied with fertilizer and manure, plus, for N, the biological N fixation and N deposition. Cultivation of N fixating crops has a large influence on the field nitrogen use efficiency. We therefore calculated a second field-NUE excluding biological N fixation. The whole-farm-NUE equals the sum of nitrogen output in beneficial products, that is, milk, meat and cash crops, divided by the sum of all nutrient inputs into the farm. Similar to the field, we calculated whole-farm-NUEs including and excluding biological N fixation. We calculated similar efficiencies for phosphorus (PUE).

2.3 Model comparison – environmental emissions and global warming impact

In addition to the whole-farm nutrient mass-balances and nutrient use efficiencies, we compared the models in terms of nutrient related emissions to the environment. Nutrient related emissions were allocated to four main farm components, i.e. animal, barn, manure management and field. Barn emissions included emissions of N_2O, NO, N_2, and NH_3 from manure deposited on the barn floor. Field emissions include all emissions associated with crops and soil, such as soil N_2O emissions due to nitrification/denitrification processes. For the field, nutrient-related emissions were allocated to specific crops. All nutrient related emissions to the environment were expressed on a per kg of compound per year basis (e.g. kg N_2O/yr). To facilitate comparison of predicted emissions with data obtained in other studies on different farms, all animal and barn-related emissions were additionally expressed on a per cow per day basis. (The average weight of animals on our farm corresponded to a reference weight of 500 kg for one animal unit). Field-related emissions were additionally expressed on a per hectare grown crop basis (e.g. kg N_2O/ha corn/yr).

We also quantified the total global warming impact of the farm. Next to N_2O emissions, we therefore collected predicted methane (CH_4) emissions for each model. 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 (GWP_{100} incl. carbon-cycle feedback (ccfb), IPCC 2013, 1 for CO_2, 34 $kgCO_2eq/kgCH_4$ and 298 $kgCO_2eq/kgN_2O$). The 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, as the CO_2 fixed by plant photosynthesis is eventually returned to the atmosphere as respired CO_2 by animals and humans, when considering the entire life cycle of dairy products (IPCC, 2006, Ch.10). The total biogenic CO_2 input was therefore assumed to balance the biogenic CO_2 output. Similar to nutrient related emissions, GHG emissions and global warming impacts were allocated to four main farm components, i.e. animal, barn, manure management, and field. For the field, GHG emissions and global warming impacts were allocated to specific crops.

2.4 Pilot farm

Input data collected for the NY State farm include herd characteristics, detailed feed scenarios per animal group, a description of feed crop cultivation practices and a description of the manure management system. These data were collected in cooperation with the farmer and the farm's nutritionist. A detailed description of farm characteristics is given in the Supporting Information (SI).

The pilot farm consists of 1096 lactating cows, 165 dry cows and 1340 replacement animals, including 250 heifer calves (SI, Table S2). The annual average milk production equaled 10,394 L/cow/year. A small percentage of this milk was fed to the heifer calves, but the largest part, i.e. 10,263 L/cow/year, was sold to the market. In addition to milk, 600 animals (300 calves and 300 cows), 90.7 metric tons manure solids and 564 metric tons wheat cash crops were exported from the farm (SI, Table S1, S8 and S9). The animals were housed in two free-stall barns. Manure was collected continuously from the two barns by an automated scraper system. The manure was collected in a reception pit and transferred to an anaerobic digester. The digestate leaving the digester was run through a solids separator to produce solids, which were partly used as bedding material in the two barns. The remaining separated solids were sold to the market or applied to cropland. The separated liquid effluent from the digester was stored in a lagoon before being applied on cropland.

The farm cultivated 982 hectares of land. The predominant soil was classified as a Honeoye silt loam (fine-loamy, mixed, active, mesic Glossoboric Hapludalfs) with gently undulating slopes and a representative gradient of 5%. Four different crops were grown on the farm: corn, winter wheat, alfalfa and grass. Corn, winter wheat and alfalfa were grown in a typical 8 year rotation cycle with 3 years corn, 1 year winter wheat and 4 years alfalfa. A crop rotation schedule was developed based on crop hectares provided by the farmer and USDA Crop Data Layer for the period 2008-2013 (SI, Table S11). In the crop rotation schedule, grass, corn silage and corn grain were continuously grown on 5%, 28.5% and 24.9% of the total area, respectively. In total 66.5% of the area was used for rotating alfalfa, corn and winter wheat in an 8 year rotation cycle. The farm produced 78% of the total animal feed dry matter. The produced feed was supplemented with purchased forage (1%), purchased grain (21% total feed dry matter) and purchased protein and mineral supplements. Detailed animal feed rations per animal group were obtained from the farm's nutritionist and are listed in Table S3 and S4 of the Supporting Information. A field management schedule was developed based on obtained data on fertilizer and manure application rates, manure composition, broad indications of fertilizer and manure application dates (e.g. 'spring' application), and crop planting dates (SI, Table S12 and S13).

To establish a whole-farm mass-balance, it was essential to provide all flows in a common unit, i.e. kg N per year for the nitrogen balance and kg P per year for the phosphorus balance. Nitrogen and P contents in milk, meat, purchased feed and harvested crops were calculated according to Cela et al. (2014). Milk protein reported to producers as true protein was converted to crude protein (CP) by multiplying by 1.075 (DePeters and Ferguson, 1992), and divided by 6.38 to obtain N concentration in milk (Higgs et al., 2012). As milk P concentrations were not reported on milk quality reports received by the producers, we used a milk P percentage of 0.09% based on work by Knowlton and Herbein (2002) to obtain the amount of P exported in milk. The nutrient content in exported animals was calculated based on the nutrient body composition of livestock (Cela et al. 2014). The nitrogen content of dairy and beef cattle was assumed to be 2.90% and 2.40% of the bodyweight, respectively. For P, the nutrient composition was 0.70% and 0.65% for dairy and beef cattle, respectively (Cela et al. 2014). Nitrogen and P contents in alfalfa silage and corn silage were determined based on actual forage test data from the pilot farm. A typical nutrient content was obtained by averaging 10 and 9 samples, for alfalfa silage and corn silage, respectively. For other produced feed, typical nutrient contents were obtained from the Cornell Net Carbohydrate and Protein System (CNCPS) feed library (Fox et al., 2004). Nitrogen and P contents in manure flows were calculated based on laboratory analyses of samples of different manure types from the farm (SI, Table S14).

3. Results

3.1 Model comparison - whole-farm nutrient balance and nutrient use efficiency

Whole farm flows. Whole-farm N and P mass-balances are shown in Figure 2. The whole-farm N mass-balances show that major N flows are internal to the farm with up to 343,199 kg N per year in feed, 269,344 kg

N per year excreted by the animals and 220,369 kg N per year applied on the field after manure management. The two dominant routes of N influx to the farm are N import in purchased feed and N fixation by alfalfa with up to 154,893 kg N purchased and another 123,330 kg N fixed per year. IFSM and ManureDNDC predicted that the greatest N flows out of the farm are N exports in milk and meat and N loss by volatilization of NH_3, in particular due to manure application on the field. Nitrate losses to groundwater are also substantial, whereas N_2O emissions were low in terms of kg N lost. These N_2O emissions, however, are important in terms of potential global warming impacts. Both IFSM and ManureDNDC predicted a large imbalance of N in soils of 29,125 and 48,043 kg N per year, respectively. Long term accumulation of soil N is unlikely, and the final destination of this N cannot be predicted.

The flow pattern is similar for phosphorus with high internal P flows of up to 49,237 kg P/year in the feed and 30,403 kg P applied as manure on the fields. Purchased feed is the major route of P import to the farm with up to 26,286 kg P purchased. The greatest flow out of the farm is P exported with milk and meat, with a maximum of 14,578 kg P per year exported. Phosphorus is predicted to accumulate in soil with 9,108 and 25,983 kg P per year based on IFSM and ManureDNDC predictions, respectively. Long-term accumulation of soil P is expected.

Comparison of nitrogen flows for each farm component and model. The model predictions of N flows by IFSM and ManureDNDC are comparable to each other, i.e. within a factor of 1.5, for most *feed, animal, barn* and *manure* related flows: milk and meat exported, manure excreted, NH_3 emissions from the barn, manure transferred from the barn to the digester and lagoon system, and N_2O and NH_3 emissions from the digester and lagoon system (Fig. 2c,e; see also Table S16 for a tabulation of all predicted N flows). The main difference between the models relates to predicted N_2O emissions from the barn. ManureDNDC predicted a N_2O emission close to 2,000 kg N for enteric N_2O emissions plus N_2O emissions from manure on the barn floor, whereas IFSM predicted an enteric N_2O emission of 158 kg N with no emission from the manure.

Specific *field* mass-balances are shown for all models, including APEX and DayCent in the Supporting Information (Fig. S1). Comparing all models on a field scale shows that the predicted total amount of N lost from the soil is comparable, i.e. within a factor of 1.7, for IFSM, ManureDNDC and APEX (range 108,594 (IFSM) – 198,085 (ManureDNDC) kg N). DayCent predicted a slightly higher N loss of 224,228 kg N /yr, when the subtracted NH_3 volatilization is included. There are, however, large differences in where and how nitrogen is lost (Fig. 3, Fig. SI-2): N loss via ammonia volatilization ranges from 23,062 kg N (APEX) to 126,625 kg N (ManureDNDC), N loss via erosion ranges from zero, i.e. not included (ManureDNDC, DayCent), to 14,203 kg N (APEX) and N loss by (de)nitrification ranges from 515 kg N (ManureDNDC) to 43,192 kg N (APEX). The difference in predicted (de)nitrification largely results from differences in predicted N_2 emissions. Predicted N_2 emissions by ManureDNDC and APEX differ by two orders of magnitude and range from 35 kg N to 42,043 kg N, respectively. Model predictions are comparable, i.e. within a factor of 1.5, to empirical crop yields (in kg N) for all models. The lowest crop yield was predicted by ManureDNDC (154,456 kg N/yr) and the greatest crop yield was predicted by IFSM (219,839 kg N/yr incl. cash crops). Model predictions are also comparable for N fixation by alfalfa, and range from 69,392 kg N fixed/yr (APEX) to 127,054 kg N fixed/yr (DayCent). Predictions of total N leaching rates are comparable, i.e. within a factor of 2, between models and are between 44,670 kg N /yr (APEX) and 91,493 kg N/yr (DayCent). An exception is the predicted N leaching for grass: on the low end APEX predicted a N leaching rate of 5 kg N/yr, whereas, on the high end, ManureDNDC predicted a N leaching rate of 2,707 kg N/yr. The slightly lower leaching rates predicted by APEX are compensated by a higher predicted N erosion loss by this model.

Comparison of phosphorus flows for each compartment and model. For phosphorus, model predictions by ManureDNDC and IFSM are highly comparable for *feed, animal, barn* and *manure* related flows: milk and meat exported, animal manure production, net manure export from the barn to the manure storage system and manure application to the field. These predicted flows are within a factor of 1.1 of each other and within a factor of 1.3 of the empirical balance.

Differences are larger for the *field* and *crop* balances (also see Fig. S1 for APEX and DayCent). IFSM and ManureDNDC deviate considerably in their predictions of the amount of P harvested with crops. IFSM predicted a total P uptake by crops of 25,147 kg, which is comparable to the empirical value of 26,588 kg P. DayCent and APEX also predicted crop P yields within a factor of 2 from empirically observed crop P yields. In contrast, ManureDNDC predicted that only 7,105 kg P is taken up by crops. The remainder of P applied to the field is mostly accumulated in the soil. Soil P accumulation predictions are similar for DayCent, IFSM and APEX, and are between 9,108 and 12,524 kg P /yr. ManureDNDC predicted a higher soil P accumulation of 25,983 kg P/yr, which is consistent with the low estimate of crop P yield by this model. According to IFSM and APEX simulations, phosphorus losses from soil to groundwater and surface water mostly occur by erosion. There is, however, a relatively large difference, i.e. a factor of 5, in predicted erosion losses by these models. Erosion P losses range from 592 kg P/yr for IFSM to 3090 kg P/yr for APEX. These erosion losses are low in comparison to the P accumulation in soil, but they may still be relevant in terms of potential eutrophication of surface waters. ManureDNDC and DayCent do not simulate erosion losses.

Nutrient use efficiencies. Table 1 shows that feed-to-milk&meat-conversion is the least efficient pathway in terms of N and P conservation with feed nitrogen use efficiencies (NUE) around 22%. Empirical and predicted feed-NUEs by IFSM and ManureDNDC are highly comparable, i.e. feed-NUEs range from 21% to 25%. Predicted field-NUEs are generally higher, above 50%, with comparable values for IFSM, DayCent and APEX, and a slightly lower value for ManureDNDC (39%). There are, however, large differences in where and how nutrients are lost (see above). In addition, field-NUEs vary depending on whether biological fixation is included in the calculation of the nitrogen use efficiency or excluded from the NUE calculation. Field-NUEs excluding biological fixation range from 63% (ManureDNDC) to 94% (IFSM); whereas, field-NUEs including biological fixation are between 39% (ManureDNDC) and 61% (IFSM). The predicted NUE for the whole-farm is model dependent. IFSM predicted a whole-farm NUE of 69% (excl. biological fixation), whereas ManureDNDC predicted a whole-farm NUE of 36%. Similar to field NUEs, whole-farm NUEs depend on the inclusion or exclusion of biological fixation. Feed phosphorus use efficiencies (feed-PUE) are comparable to feed NUEs and range from 27% to 31% (Table 1). Predicted field-PUEs range from 20% (ManureDNDC) to 72% (IFSM) and are more variable than predicted field-NUEs. This is partly due to large differences in crop yield and uptake of P, specifically due to the low crop P removal predicted by ManureDNDC. Accordingly, IFSM predicted a whole-farm NUE of 72% and ManureDNDC predicted a whole-farm NUE of only 30%. Next to crop yields, the higher efficiency predicted by IFSM is partly related to higher exports of cash crops as included by IFSM.

3.2 Model comparison - environmental emissions and global warming impact

NH_3 emissions. Predicted ammonia emissions, expressed in kg ammonia emitted per year, for the whole-farm are between 90,791 (IFSM) and 192,490 kg NH_3/yr (ManureDNDC) (Fig. 3a). Barn ammonia emissions are highly comparable, i.e. with a factor of 1.5, between IFSM (21,933 kg NH_3/yr; 25 g NH_3/cow/day) and ManureDNDC (26,431 kg NH_3/yr; 30 g NH_3/cow/day). Predicted ammonia emissions from the digester and manure storage are comparable between IFSM and ManureDNDC, and amount to 19,464 and 12,300 kg NH_3/yr, respectively. Ammonia emissions from manure application on the field dominate whole-farm ammonia emissions, although model specific differences are found in the magnitude of this flow. Field ammonia emissions range from only 10% of total N-applied in manure and mineral fertilizer lost as NH_3 for APEX (28,004 kg NH_3/yr) to 51% lost as NH_3 for ManureDNDC (154,000 kg NH_3/yr), with an intermediary value of 19% loss for IFSM (49,393 kg NH_3/yr).

N_2O emissions. Predicted N_2O whole-farm emissions, expressed in kg nitrous oxide emitted per year, are similar for IFSM and ManureDNDC with predictions of total N_2O emitted of 5,169 kg N_2O/yr and 4,985 kg N_2O/yr, respectively. Larger differences are, however, observed in component-specific emissions (Fig. 3b). For ManureDNDC, the greatest N_2O emissions occur in the *barn* with 3,080 kg N_2O/yr (3.5 g N_2O/cow/day), whereas IFSM predicted very low barn emissions (248 kg N_2O/yr or 0.3 g N_2O/cow/day). Predicted N_2O emissions from the field are highly variable across models, ranging from only 0.1 % of N-applied lost as N_2O (ManureDNDC) to 2.7% of N-applied lost as N_2O (DayCent). Intermediary values of 0.5% and 1.3% of applied N lost as N_2O were found for APEX and IFSM, respectively. On a per crop basis, all models predicted a dominant contribution of corn to total N_2O emissions from the field (Fig. 3b). This is partly due to the large corn land area. Comparing crop-specific N_2O emissions on a per hectare basis (Table S19) shows that N_2O emissions are generally greatest for corn, with emissions ranging from 0.4 kg N_2O/ha (ManureDNDC) to 15.2 kg N_2O/ha (DayCent). N_2O emissions are intermediary for alfalfa and for wheat. For alfalfa, N_2O emissions range from 0.4 kg N_2O/ha (Manur-

eDNDC) to 3.8 kg N_2O/ha (DayCent). For wheat, N_2O emissions range from 0.3 kg N_2O/ha (ManureDNDC) to 4.2 kg N_2O/ha (DayCent). Predicted N_2O emissions are smallest for grass and ranged from 0.001 kg N_2O/ha (APEX) to 1.2 kg N_2O/ha (DayCent).

Nitrate and organic N loss to water. On a per crop basis, corn dominates the loss of N from soil to water sources in all models (Fig. 3c). This dominance remains when crop-specific N losses are expressed on a per hectare basis (Table S19). Model predictions of total N loss to groundwater were highly similar, i.e. within a factor of 1.5, with total losses between 59,572 kg N/yr for IFSM (26% of applied fertilizer plus manure N) and 91,493 kg N/yr for DayCent (41% of applied fertilizer and manure N). All models predicted that leaching was the dominant pathway of N loss to water (SI, Fig. S2a), but predicted contributions of run-off and erosion differ between the models. According to IFSM, DayCent and ManureDNDC, erosion and run-off contribute negligibly to total N loss to water. In contrast, APEX predicted a contribution of erosion and run-off to total N loss to water of 20% and 18%, respectively.

Phosphate loss to water. All models predicted that P losses occurred predominantly from corn, but large differences occurred in the values of predicted P losses from soil to water, depending on the considered removal pathways (Fig. 3d). On the low end, DayCent predicted a total P loss from soil of 21 kg P/yr). On the high end, APEX predicted a loss of 3,572 kg P/yr, predominantly due to a higher predicted P loss with soil erosion. ManureDNDC and IFSM predicted intermediary P-losses of 294 and 724 kg P/yr.

Table 1. Nutrient use efficiencies (NUE and PUE)

Nutrient	**Nutrient Use Efficiency**	**Empirical**	**IFSM4.2**	**ManureDNDC**	**DayCent4.5**	**APEX0806**
N	Feed-NUE	21.4%	24.5%	21.5%		
	Field-NUE$_{\text{with N fixation}}$		61.4%	38.8%	56.7%	53.4%
	Field-NUE$_{\text{w/o N fixation}}$		93.6%	63.0%	91.3%	69.3%
	Whole-farm-NUE$_{\text{with N fixation}}$[a]	*36.2%*	38.5%	20.4%[b]		
	Whole-farm-NUE$_{\text{w/o N fixation}}$[a]	*44.1%*	68.6%	35.9%[b]		
P	Feed-PUE	26.9%	31.2%	27.1%		
	Field-PUE		71.7%	20.1%	66.2%	53.5%
	Whole-farm-PUE[a]	*50.9%*	62.1%	30.0%[a]		

a. Manure export is not included in the nutrient efficiency calculation. b. To calculate the whole-farm NUE for ManureDNDC, 'crop uptake of P' is subtracted from 'feed P' to determine required P from 'purchased feed'.

Global warming impact. Predicted whole-farm, global warming impacts are very similar for IFSM and ManureDNDC with a predicted global warming impact of approximately $1.1 \cdot 10^7$ kg CO$_2$eq./year for both models (Fig. 4). Predicted enteric CH$_4$ emissions dominate GHG impacts at the individual farm level. Enteric CH$_4$ emissions are very similar for IFSM and CNCPS, i.e. $2.4 \cdot 10^5$ and $2.7 \cdot 10^5$ kgCH$_4$/year, respectively, leading to a GHG contribution of $8.3 \cdot 10^6$ and $9.0 \cdot 10^6$ kg CO$_2$eq./year, respectively. Predicted enteric CH$_4$ emissions by ManureDNDC are slightly less, i.e. factor of 2.0, than predictions by IFSM and CNCPS. However, ManureDNDC predicted a higher contribution of emissions from manure on the barn floor to the total barn methane emission.

IFSM and DayCent both predicted an important contribution (12% - 24% based on total GWP predicted by IFSM) of N$_2$O emissions from cropland to the total global warming potential. In contrast, ManureDNDC predicted N$_2$O emissions from fields to contribute negligibly (0.01%) to total global warming potentials. N$_2$O emissions from the barn floor are, however, a non-negligible contributor to greenhouse gas impacts (8.5% contribution) according to ManureDNDC.

4. Discussion

4.1 Model comparison

Model predictions are comparable for nutrient flows related to the *animal*, i.e. milk&meat production, enteric emission of methane and nitrous oxide, and manure production, suggesting that the animal system is well-understood. This observation is consistent with results from previous model evaluation studies. In previous studies, IFSM simulated dry matter (DM) and N excretions accurately represented individual cow and herd excretions (Rotz et al. 1999, Rotz et al. 2006). Similarly, Higgs et al. (2012) showed that CNCPS accurately (r^2=0.96) predicted total manure N excretion from lactating dairy cows. CNCPS predictions of enteric methane emissions also were not significantly different from measured data obtained in metabolic chamber experiments. An evaluation of ManureDNDC with measurements of CH_4 concentrations in a feed cell and a free-stall barn showed that model predictions of CH_4 fluxes were comparable both in temporal trend and in magnitude with empirical fluxes (Li et al. 2012).

For the *barn* component, our results show that predictions of barn NH_3 emissions are highly similar for IFSM and ManureDNDC. This is not unexpected as comprehensive field evaluation studies have shown that both models accurately predict barn NH_3 emissions in terms of temporal trend and in magnitude (Rotz et al. 2014; Li et al. 2012; Deng et al. 2015). These evaluation studies were partly performed with empirical data obtained for our pilot farm (Rotz et al. 2014; Deng et al. 2015). As part of the National Air Emissions Monitoring Study (NAEMS) program, Bogan et al. (2010) determined NH_3 emissions in one of the two barns of the pilot farm. The yearly average, observed NH_3 emission was 43.2 g/NH_3/cow/day for a barn with 470 lactating cows. To compare this empirical observation with the predicted barn NH_3 emissions for the entire farm, these measured data were adjusted per animal unit of 500 kg/AU, which corresponded to the average weight of all animals at the pilot farm. This results in an empirical average NH_3 emission of 34 gNH_3/cow/day. Predicted barn ammonia emissions for IFSM (25 gNH_3/cow/day) and ManureDNDC (30 gNH_3/cow/day) are within a factor of 1.4 of the observed value and correspond well to the empirical data.

A large difference was found in model predictions for barn N_2O emissions. ManureDNDC predicted a substantial emission of N_2O from the barn floor, whereas in IFSM simulations barn N_2O emissions were negligible. This difference is attributable to a difference in model assumptions. In IFSM, N_2O emissions from manure are negligible when manure is removed from the barn within a few hours of excretion, which is supported by limited measurements of N_2O concentrations in a free stall barn (Chianese et al. 2009). The rationale is, that manure does not stay in the barn long enough for substantial nitrification and denitrification processes to occur. An evaluation of ManureDNDC with limited observation data showed that model predicted N_2O fluxes were in agreement with field measurements for a free stall barn (Li et al. 2012). While this may indicate that ManureDNDC is capable of predicting total N_2O emissions in the barn, it does not provide information on the importance of manure N_2O emissions in comparison to enteric N_2O emissions. A further investigation of the relevance of manure N_2O emissions in a free stall barn where manure is removed very soon after excretion is needed. This is appears important, as, according to ManureDNDC, barn N_2O emissions can contribute substantially to the whole-farm global warming impact.

For the *manure management* system, predicted nutrient-related emissions were highly comparable between IFSM and ManureDNDC. A minor exception was the predicted emission of N_2. Predicted N_2 emissions were 3 times higher in ManureDNDC than in IFSM. From an environmental perspective, this difference is irrelevant as N_2 is a natural, non-reactive component of the atmosphere. This loss of N does, however, affect the whole farm balance.

Field nutrient flows are much more variable across models. Two issues stand out. First, compared to the other models, ManureDNDC predicted very high NH_3 volatilization from soil. In contrast, ManureDNDC underpredicted soil N_2O emissions compared to the other models. These differences result from predicted changes in the manure composition due to anaerobic digestion by ManureDNDC. During anaerobic digestion, temperature-dependent hydrolysis reactions convert stable organic matter into more easily degradable C compounds. As a consequence, the amount of easily degradable C compounds added to the soil upon manure application is reduced, which, in turn, reduces denitrification rates and thus N_2O emissions. In addition, while the manure organic C transforms to DOC, CO_2 or CH_4, the organic N transforms to NH_4 (Li et al. 2012). Upon field application of manure, this increased amount of ammonium-N is partly converted to ammonia, which causes a higher ammonia volatilization rate and a lower N_2O emission rate, as less ammonium is available for nitrification and subsequent denitrification. The effects of anaerobic digestion on organic carbon pools in manure are presently not simulated by APEX and DayCent. IFSM removes digested carbon, i.e. CO_2 and CH_4 generated during anaerobic digestion, from the manure, but it does not simulate differences in the forms (i.e. stability) of organic carbon. Exclusion of the digester from the manure management train (lagoon only), results in a higher predicted N_2O emission by ManureDNDC of 901.50 kg N_2O-N /yr, which is more comparable to emission estimates by IFSM (lagoon only, 2923.5 kg N_2O-N/yr), although still somewhat lower. At present, the effects of anaerobic digestion on manure composition and emissions after field application are not well understood. In a recent review on effects of anaerobic digestion on environmental emissions, Möller (2015) concluded that "the direct effects of anaerobic digestion on field level emissions (NH_3− and N_2O− emissions, NO_3 - leaching) are negligible or at least ambiguous". For N_2O, "most findings indicate a reduction of the soil-borne N_2O emission after application of digestates in comparison to the undigested feedstocks, however the effects are influenced by several environmental conditions, incl. soil water content, soil type and soil organic matter content" (Möller, 2015). Second, for both N and P, there is large variability in predicted nutrient losses to the hydrosphere. Overall, APEX predicted larger losses of N and P due to erosion and run-off than the other models. This difference is particularly striking for P. Phosphorus erosion losses range from 0 (DayCent, ManureDNDC) to 3090.1 kg P /yr (APEX). ManureDNDC does not explicitly model erosion losses, but incorporates these losses into the run-off rate. At present, the DayCent model does not account for slope and erosion and is thus a poor model for P dynamics at the landscape scale. For all field emissions, predictions of the whole-farm model IFSM fall in the range of the other models.

All models predicted a relatively high amount of unaccounted N in soil. Long-term storage of N in soil pools is not considered realistic. Rather the 'unaccounted' soil N results from a continuous over application of manure and fertilizer N on cropland, particularly on corn fields. This N will eventually disappear from the system by leaching, erosion, run-off and/or gaseous losses. The final fate and form is difficult to predict with our current models.

4.2 Implications and recommendations

The whole-farm mass-balance approach is advocated as an essential tool to assess and improve the sustainability of dairy production systems. Currently, whole-farm mass-balance studies often focus on one nutrient, mainly nitrogen, sometimes in combination with an assessment of GHG impacts. Here, we present a whole-farm mass-balance for a dairy farm in NY that includes both N and P flows and an assessment of the global warming potential. Our results 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 emissions contribute 25% of the total C footprint of the dairy supply chain. In addition, Del Prado et al (2013) found that enteric CH_4 and crop land N_2O were the main contributors to whole-farm greenhouse gas impacts for grassland ruminant-based farm systems in Europe, although large site- and farm-specific variations were observed. In terms of nutrient use efficiency, the feed-to-milk&meat-conversion is also the least efficient pathway in terms of N and P conservation. This highlights the importance of the animal component in improving the sustainability of this particular dairy farm.

Our comparison of five process-based models provides insight in the range of expected emissions associated with milk production. Model predictions are highly comparable for nutrient emissions related to the animal, i.e. enteric emission of methane and nitrous oxide, and NH_3 emissions from the barn. A large range in predicted emissions is obtained for N_2O emissions from the barn. Further model validation is required comparing empirical data of manure N_2O emissions in a free stall barn, as a function of manure handling strategies, to model predictions. Predicted field emissions of N_2O and NH_3, and N and P losses to the hydrosphere, are largely variable across models. This indicates that there is a need to further our understanding of soil and crop nutrient flows and that measurement data on nutrient emissions are particularly needed for the field. In addition, there is a need to further understand how the anaerobic digester influences the manure composition and subsequent emissions of N_2O and NH_3 after application of the digestate to the field. Empirical data on manure composition before and after anaerobic digestion are essential for model evaluation.

Our model comparison study has implications for farm-gate Life Cycle Assessment (LCA) studies that aim to evaluate GHG mitigation and nutrient efficiency optimization strategies of dairy production systems. This study first highlights the importance to use whole farm models to account for the interdependence between emission flows in the different farm compartments. Our results suggest that the animal, barn and manure management system, is relatively well understood and that process-models can be used to quantify GHG and nutrient-based emissions for these farm components. An exception is the prediction of N_2O emissions from the animal and barn, as discussed above. At present, estimates of field related emissions are more variable and a detailed comparison with advanced measured flows is required to further enhance and test model accuracy for field-based emissions and to select the most appropriate models to predict emissions for the field.

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6. References

Bogan, B.W., Chandrasekar, A., McGlynn, S., Gooch, C.A., Heber, A.J. 2010. National Air Emissions Monitoring Study: Data from dairy freestall barn and milking center in New York, Site NY5B. Final Report. Purdue University, West Lafayette, IN.

Bouwman, L., Klein Goldewijk, K., Van der Hoek, K.W., Beusena, A.H.W., Van Vuuren, D.P., Willems, J., Rufino, M., Stehfest. E, 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. PNAS 110, 20882-20887.

Cela, S., Kettering, Q.M., Czymmek, K., Soberon, M., Rasmussen, C., 2014. Characterization of nitrogen, phosphorus, and potassium mass balances of dairy farms in New York State. J. Dairy Sci. 97, 7614-7632.

Chianese, D.S., Rotz, C.A., Richard, T.L., 2009. Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. Trans. ASABE 52, 1325-1335.

Davidson, E.A., David, M.B., Galloway, J.N., Goodale, C.L., Haeuber, R., Harrison, J.A., Howarth, R.W., Jaynes, D.B., Lowrance, R.R., Nolan, B.T., Peel, J.L., Pinders, R.W., Porter, E., Snyder, C.S., Townsend, A.R., Ward, M.H., 2012. Excess nitrogen in the US environment: Trends, risks and solutions. ESA Issues Ecol. 15, 1-16

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S., Schimel, D.S., 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: Schaffer, M., Ma, L., Hansen, S. (Eds.), Modeling Carbon and Nitrogen Dynamics for Soil Management, CRC Press, Boca Raton, Florida, pp. 303-332.

Del Grosso, S.J., Ojima, D.S., Parton, W.J., Mosier, A.R., Peterson, G.A., Schimel, D.S., 2002. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. Environ. Pollut. 116, S75-S83.

Del Grosso, S.J., Mosier, A.R., Parton, W.J., Ojima, D.S., 2005. DAYCENT model analysis of past and contemporary soil N_2O and net greenhouse gas flux for major crops in the USA. Soil Tillage Res. 83, 9-24.

Del Grosso, S.J., Halvorson, A.D., Parton, W.J., 2008a. Testing DAYCENT model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. J. Environ. Qual. 37, 1383–1389.

Del Grosso, S.J., Parton, W.J., Ojima, D.S., Keough, C.A., Riley, T.H., Mosier, A.R., 2008b. DayCent simulated effects of land use and climate on county level N loss vectors in the USA, in: Hatfield, J.L., Follet, R.F. (Eds.), Nitrogen in the environment: sources, problems and management. Academic Press / Elsevier, Amsterdam, Boston, 571-595.

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

Deng, J., Li, C., Wang, Y., 2015. Modeling ammonia emissions from dairy production systems in the United States. Atmos. Environ. 114, 8-18.

DePeters, E.J., Ferguson, J.D., 1992. Nonprotein nitrogen and protein distribution in the milk of cows. J. Dairy Sci. 75, 3192–3209.

Dijkstra, J., Oenema, O., Bannink, A., 2011. Dietary strategies to reducing N excretion from cattle: implications for methane emissions. Curr. Opin. Environ. Sustainability 3, 414-422.

FAO, 2010. Greenhouse gas emissions from the dairy section. A life cycle assessment. Food and Agricultural Organization of the United Nations (FAO). www.fao.org/docrep/012/k7930e/k7930e00.pdf

Fox, D.G., Tedeschi, L.O., Tylutki, T.P., Russell, J.B., Van Amburgh, M.E., Chase, L.E., Pell, A.N., Overton, T.R., 2004. The Cornell Net Carbohydrate and Protein System model for evaluating herd nutrition and nutrient excretion. Anim. Feed Sci. Technol. 112, 29–78.

Gassman, P.W., Williams, J.R., Wang, X., Saleh, A., Osei, E., Hauck, L.M., Izaurralde, R.C., Flowers, J.D., 2010. The agricultural policy/environmental extender (APEX) model: An emerging tool for landscape and watershed environmental analyses. Am. Soc. Agri. Biol. Eng. (ASABE) 53, 711-740.

Giltrap, D.L., Li, C., Saggar, S., 2010. DNDC: A process-based model of greenhouse gas fluxes from agricultural soils. Agric. Ecosyst. Environ. 136, 292-300.

Henderson, A., Asselin, A., Heller, M., Vionnet, S., Lessard, L., Humbert, S., Saad, R., Margni, M., Thoma, G., Matlock, M., Burek, J., Kim, D.S., Jolliet, O., 2013. Comprehensive Life Cycle Assessment of Fluid Milk in the United States. Final Report, University of Michigan

Higgs, R.J., Chase, L.E., Van Amburgh, M.E., 2012. Development and evaluation of equations in the Cornell Net Carbohydrate and Protein System to predict nitrogen excretion in lactating dairy cows. J. Dairy Sci. 95, 2004-2014.

Higgs, R.J., Russomanno, K.I., Christoph, T.F., Van Amburgh, M.E., 2013. Predicting methane and carbon dioxide emissions using the CNCPS. J. Dairy Sci. 96, (E-Suppl. 1), 598 (Abstr.)

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., Tanabe K. (Eds). IGES, Japan.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jarecki, M.K., Parkin, T.B., Chan, A.S.K., Hatfield, J.L., Jones, R., 2008. Comparison of DAYCENT-simulated and measured nitrous oxide emissions from a corn field. J. Environ. Qual. 37, 1685-1690.

Knowlton, K.F., Herbein, J.H., 2002. Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content. J. Dairy Sci. 85, 1227-1236.

Li, C., Salas, W., Zhang, R., Krauter, C., Rotz, A., Mitloehner, F., 2012. Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutr. Cycl. Agroecosyst. 93, 163-200.

Möller, K. 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. Agron. Sustain. Dev. 35, 1021-1041.

NRC, 2003. Air emissions from animal feeding operations: Current knowledge, future needs. National Research Council, Ad Hoc Committee on Air Emissions from Animal Feeding Operations, Washington, DC

Oenema, O., Witzke, H.P., Klimont, Z., Lesschen, J.P., Velthof, G.L. 2009. Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. Agriculture Ecosystems Environ. 133, 280-288.

Pelletier, N., Tyedmers, P., 2010. Forecasting potential global environmental costs of livestock production 2000-2050. PNAS 107, 18371-18374.

Rotz, C.A., Mertens, D.R., Buckmaster, D.R., Allen, M.S., Harrison, J.H., 1999. A dairy herd model for use in whole farm simulations. J. Dairy. Sci. 82, 2826–2840.

Rotz, C.A., Oenema, J., van Keulen, H., 2006. Whole farm management to reduce nutrient losses from dairy farms: A simulation study. Appl. Eng. Agriculture 22, 773 – 784.

Rotz, C.A., Montes, F., Chianese, D.S., 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93, 1266-1282.

Rotz, C.A., Corson, M.S., Chianese, D.S., Montes, F., Hafner, S.D., Jarvis, R., Coiner, C.U., 2012. Integrated Farm System Model: Reference manual. USDA Agricultural Research Service, University Park, PA. https://www.ars.usda.gov/Main/docs.htm?docid=21345

Rotz, C.A., Montes, F., Hafner, S.D., Heber, A.J., Grant, R.H., 2014. Ammonia emission model for whole farm evaluation of dairy production systems. J. Environ. Qual. 54, 1143-1158.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Šebek, L.B.J., 2005. A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. Nutr. Cycl. Agroecosyst. 71, 163-175.

Schils, R.L.M., Olesen, J.E., del Prado, A., Soussana, J.F., 2007. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livestock Sci. 112, 240–251.

Schindler, D.W., Hecky, R.E., Findlay, D.L., Stainton, M.P., Parker, B.R., Paterson, M.J., Beaty, K.G., Lyng, M., Kasian, S.E.M., 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. PNAS. 105, 11254-11258.

Steiner, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., De Haan, C., 2006. Livestock's long shadow. Environmental issues and options. Food and Agricultural Organization (FAO) of the United Nations, Rome. www.fao.org/docrep/010/a0701e/a0701e00.HTM

Thoma, G., Popp, J., Nutter, D., Shonnard, D., Ulrich, R., Matlock, M., Kim, D.S., Neiderman, Z., Kemper, N., East, C., Adom, F., 2013. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. Int. Dairy. J. 31, S3-S14.

Tylutki, T.P., Fox, D.G., Durbal, V.M., Tedeschi, L.O., Russell, J.B., Van Amburgh, M.E., Overton, T.R., Chase, L.E., Pell, A.N., 2008. Cornell Net Carbohydrate and Protein System: A model for precision feeding of dairy cattle. Animal. Feed. Sci. Technol. 143, 174-202.

Van Amburgh, M.E., Chase, L.E., Overton, T.R., Ross, D.A., Recktenwald, E.B., Higgs, R.J., Tylutki, T.P., 2010. Updates to the Cornell Net Carbohydrate and Protein System v6.1 and implications for ration formulation. Proc. Cornell Nutr. Conf., Syracuse, NY. pp: 144-159.

Williams, J.R., Izaurralde, R.C., Steglich, E.M., 2012. Agricultural Policy/Environmental eXtender Model, Theoretical Documentation. Version 0806, Texas A&M AgriLife, Texas.