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Comparison of process-based models to quantify nutrient flows and greenhouse gas emissions associated with 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 to reveal trade-offs between emissions of the different greenhouse gases (GHG) and nutrient-based pollutants and to ensure that interactions between farm components are taken into account. Process-based models are essential to support whole-farm mass balance accounting. However, since variation between process-based model results can be large, 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 predicted carbon (C), nitrogen (N) and phosphorus (P) flows and potential global warming impact (GWI) associated with milk production at the animal, field and farm-scale. We include two whole-farm models complemented by two field-scale models and one animal-based model. A whole-farm mass-balance framework was used to facilitate model comparison at different scales. GWIs were calculated from predicted emissions of methane (CH_4) and nitrous oxide (N_2O) and soil C change. Results show that predicted whole-farm GWIs were similar for the two whole farm models, ManureDNDC and IFSM, with a predicted GWI of 9.3 and 10.8 Gg CO_2eq. year^{-1} for ManureDNDC and IFSM, respectively. Enteric CH_4 emissions were the single most important source of greenhouse gas emissions contributing 47%–70% of the total farm GWI. Model predictions were comparable, that is, within a factor of 1.5, for most flows related to the animal, barn and manure management system. In contrast, predicted field emissions of N_2O and ammonia (NH_3) to air, N and P losses to the hydrosphere and soil C change, were highly variable across models. This indicates that there is a need to further our understanding of soil and crop N, P and C flows and that measurement data on nutrient and C flows are particularly needed for the field. In addition, there is a need to further understand how anaerobic digestion influences manure composition and subsequent emissions of N_2O and NH_3 after application of digestate to the field. Empirical data on manure composition before and after anaerobic digestion are essential for model evaluation.

1. Introduction

The livestock production sector is a key contributor to 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

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through greenhouse gas (GHG) emissions. The global dairy sector is reportedly responsible for 2.7% of global GHG emissions (FAO, 2010). In the US, the dairy sector is responsible for approximately 1.9% of GHG emissions (Thoma et al., 2013). In addition, crop-livestock production systems are the largest cause of human alteration of global nitrogen (N) and phosphorus (P) cycles (Bouwman et al., 2013), 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, P is a limited resource, and sustaining an adequate P supply is a major emerging challenge (Cordell and White, 2014).

Assessing and improving the sustainability of dairy production is essential to secure future food production. This is, however, challenging for several reasons. First, in nonhomogeneous countries like the US, milk production practices and climatic conditions vary widely, which can result in large farm-specific variations in GHG emissions and nutrient losses (Del Grosso et al., 2005; Henderson et al., 2013). Second, in dairy production systems, N, P and carbon (C) flows are interrelated. Consequently, mitigation of one pollutant can increase emissions of another pollutant. For example, Dijkstra et al. (2011) suggested that dietary strategies that reduce N excretion from dairy cows may increase enteric 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 component of this nutrient cycle can have major effects on nutrient flows to or from other farm components.

Understanding trade-offs between emissions of GHGs and nutrients ensures that interactions between N, P and C cycling and 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) Tier 1 emission factors to quantify nutrient and GHG emissions. These emission factors are often based on rough emissions estimates and cannot account for temporally and spatially-explicit variations. IPCC Tier 2 methods are more advanced, particularly for livestock, and GHG emissions can be predicted based on animal activity data, diet characteristics and livestock type. This provides a more spatial-explicit characterization of these flows. However, IPCC methods were primarily developed to quantify GHG emissions rather than to quantify flows of N- and C-based compounds. Also, as there are no P-based GHGs, the IPCC methods are not directly applicable to quantify P losses. Thus, IPCC Tier 1 and Tier 2 methods neither consider nutrient cycling between different farm components nor account for interactions between N, P, and C flows. From a sustainability perspective this may mask nutrient and carbon imbalances, resulting in unaccounted nutrient and/or carbon losses or gains at animal, field or farm scales. Reliance on IPCC Tier 1 or Tier 2 methods may also result in sub-optimal improvements when trade-offs occur. Finally, it is generally thought that the environmental performance of dairy farms can be improved by improving nutrient cycling efficiency across farm components, and subsequently reducing nutrient losses.

A whole-farm, holistic approach explicitly considers nutrient cycling across farm components (e.g., Schils et al., 2005, 2007). It includes a mass-balance analysis that considers nutrient imports to the farm, exports from the farm, and internal nutrient flows between farm components. It is a powerful methodology to develop GHG mitigation strategies for farming systems (e.g., Schils et al., 2005, 2007; Del Prado et al., 2013). Parameterization of a whole-farm mass-balance is challenging because it is difficult, relatively inaccurate, and expensive to measure the assimilation and emission of GHGs and to empirically determine internal nutrient flows at the whole-farm scale (Rotz et al., 2010). Process-

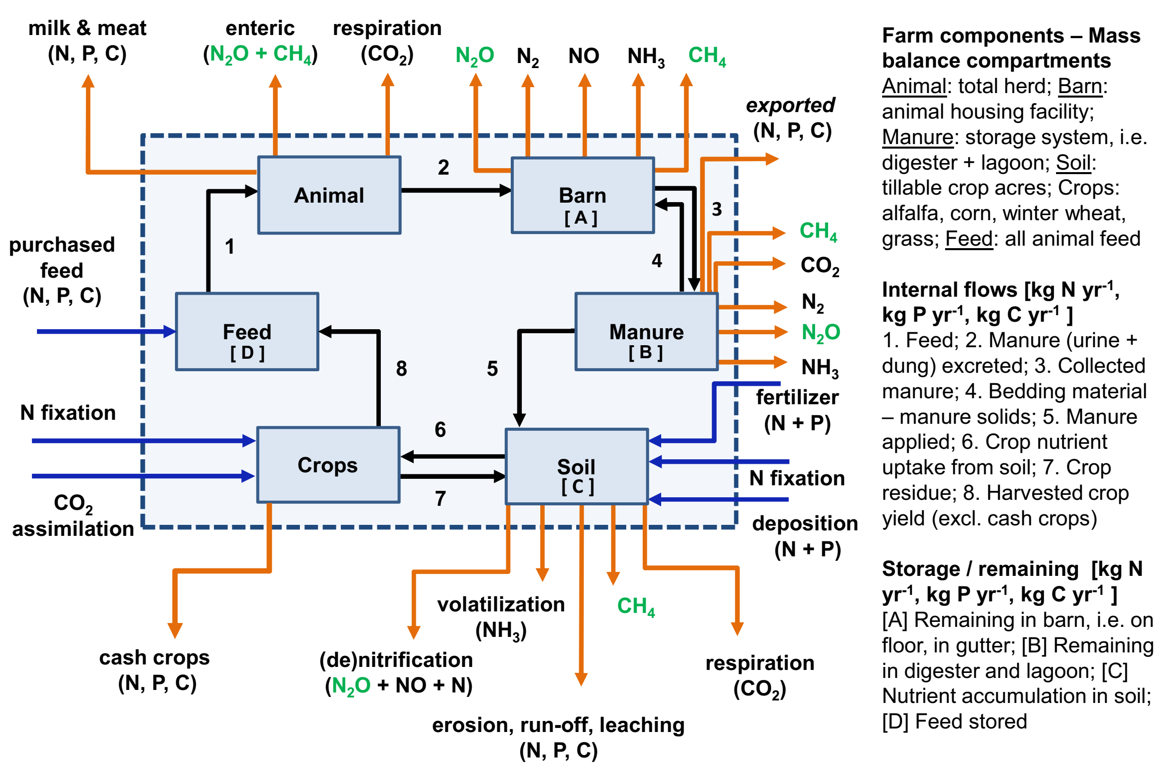

Fig. 1. Whole-farm mass-balance framework for considered nutrient and carbon flows. All nutrient flows in kg N yr^{-1} or kg P yr^{-1} and all carbon flows in kg C yr^{-1}. Black arrows represent internal nutrient flows, blue arrows represent nutrient and/or carbon inflows to the farm whereas orange arrows represent nutrient and/or carbon losses from the farm. To quantify global warming impacts, next to soil C change, emissions of 2 greenhouse gases were considered, N2O and CH4, which are indicated in green letters.