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Report detailing the selection of the sub- models for NitroScape. The report will emphasize the adaptation of each mode to NitroScape perspective and relation between models

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Farm scale modelling in NitroEurope C4

Introduction

When attempting to understand and predict N fluxes in agriculture, it is important to consider that the interactions between N losses occur over a range of scales and vary considerably, depending upon the type of farming. Likewise, the opportunities for management to affect N flows vary between farm types. On arable farms with no livestock, the interactions are mainly at the field scale but as livestock density increases, the farm scale becomes increasingly important. Much N is transferred from field to animal housing in plant products used as animal feed. Most of this is excreted as dung and urine, which passes as manure through a collection and storage system, before being returned to the fields. At each point along this route, there are opportunities for N to be lost to the environment. The interactive nature of N flows is particularly true for cattle farms; the range of management options is large, a large proportion of the animal feed is normally home-grown and the N content of forage crops varies more widely than for grain crops.

The farm model in NitroScape needs to consider both the farm level N fluxes and losses, and the modelling of farm level management, which will influence inputs to the other NitroScape models. There are a number of existing models, most of which only covers parts of the farm fluxes or management issues.

Modelling farm level flows and fluxes

Inputs for livestock systems comprise those of biogenic origin like manures or biological N fixation by legumes, but also industrially manufactured inputs like compound feeds and fertilisers. The outputs are generally milk and meat products. However, in some intensive systems manure surpluses have to be exported from the farm as well. Emissions occur at several stages within the nutrient cycle.

The farm level flows and fluxes include the following components:

- Livestock, with feed intake, production of meat and milk, reproduction and manure production. This also includes estimates of CH_4 and CO_2 production by the animals.
- Manure storage, both in-house and outside. The must also include model of C and N turnover in the storage, including emissions of NH_3, N_2O, N_2, CH_4 and possibly N_2O.
- Feed storages. These feed storages may be used as buffers for storing on-farm production or imported goods. Most important is probably the modelling of silage, where some emissions of both C- and N-containing compounds may occur.

The level of detail in the modelling depends on the objective of the research. With respect to farm modelling choices to be made are related to:

- The number of farm components. As stated above both animal and a soil-crop components are essential for ruminant livestock systems. A typical cycle used in N studies comprises components animal-manure-soil-crop (Aarts et al., 2000), but further sub-divisions are possible.
- The system boundaries. In whole-farm approaches the system within the farm gate is the minimum that should be studied. However, emissions related to the production of inputs or the

consumption of outputs are not accounted for. Efficiency indicators derived from a farm gate approach may therefore not represent the complete picture (Schroder et al., 2003). Therefore it can be justified to include pre- and post-chain effects into the whole-farm approach.
- The simulation methodology. Whole-farm models are usually a diverse mix of empirical and mechanistic modelling, with more or less reliance on one of them. Whole-farm models are often developed through the combination of existing sub-models, which may have different underlying simulation methodologies. With respect to GHG, emissions can be calculated with emission factors, comparable to the IPCC methodology, or simulated with mechanistic (sub)models.
- The aspects to be studied. The NitroScape model will focus on nitrogen and GHG emissions. However, this can be extended with aspects such as phosphorus, energy use, heavy metals, landscape, biodiversity, animal welfare and milk or meat quality. Inclusion of financial evaluation of mitigation options is a must, when it comes to potential implementation by farmers. Some models generate farm plans in which the financial margin is maximised (Berntsen et al., 2004; Evert et al., 2003; Gibbons et al., 2006), enabling identification of economically optimal methods for emission reduction.

Modelling farm management

Farm management greatly influences both crop and livestock performance and the modelling of this is therefore also important for farm N flows and fluxes. It is possible in many cases to assume fixed or observed management. However, with respect to some mitigation scenarios, it would be useful for the NitroScape farm model to be able to estimate the optimal management under a given range of constraints. Such management issues include:
- Removal of manure from the in-house manure storage to outside storages/heaps.
- Timing of fertiliser and manure applications to the soil.
- Timing of field operations, including tillage, sowing and harvesting.
- Grazing of animals (period and duration per day)
- Replacement of older animals by young stock
- Import of feed
- Export of manure

Available models

A small review of some of the existing farm scale models has been made, and their main features are outline below. The review is not meant to be exhaustive and the models have primarily been selected based on their ability to simulate N fluxes and greenhouse gas emissions. The main characteristics of these models are summarised in Table 1.

DairyWise

DairyWise is an existing empirical model integrating all major subsystems of a dairy farm into one whole-farm model (van Alem and van Scheppingen, 1993). The model is used extensively in research, consultancy and teaching for technical, environmental and financial simulations of dairy farms. To operate DairyWise, input data are required which are classified into several categories such as general farm management, soil characteristics, herd type and feeding management, cropping plan, grass and forage management, buildings and machinery. The key sub-models of DairyWise are the GrassGrowth model and the DairyHerd model. The GrassGrowth model predicts the daily growth and quality of grass as a function of soil type, N application and previous management. The DairyHerd model predicts daily feed intake and milk production of a complete dairy herd, including young stock. In the next step the FeedSupply model combines the herd requirements in terms of energy and protein with the supply of homegrown grass and other forage crops and imported compound feeds. The output of the FeedSupply model contains all data for a year-round feeding plan. Together with additional inputs, the output of the FeedSupply model serves as the input for technical, environmental and economic sub-models. The sub-model Nutrient cycling simulates all internal and external flows of nitrogen, potassium and phosphorus (P). The nitrogen farm gate surplus is partitioned among ammonia, nitrate and nitrous oxide losses. Other ecological sub-models involve the calculation of energy use, the integration of nature protection schemes or the implementation of organic farming.

Recently, a GHG module has been added in which CH_4, N_2O and CO_2 emissions are calculated with refined emission factors (Schils et al., 2006). The CH_4 emission from enteric fermentation is calculated with emission factors per kg DM uptake, distinguishing between concentrates, grass products and maize silage. Emission from manure is calculated separately for stored manure and manure excreted during grazing. According to the IPCC guidelines, DairyWise distinguishes between direct and indirect N_2O emissions, related to later denitrification of leached nitrate. Direct emissions are calculated with emission factors for N inputs through fertiliser, biological fixation, manure application, urine excreted during grazing, crop residues and peat oxidation. Furthermore, the model calculates an additional N_2O emission when grassland is ploughed. The emission factors are refined for three categories of ground water level and for two soil types (mineral and organic). The indirect N_2O emissions are calculated with emission factors from the modelled nitrate and ammonia emissions. The direct carbon dioxide (CO_2) emission are calculated from the on-farm use of diesel and gas, while the indirect CO_2 emissions are calculated for the use of electricity, the import of feed and fertiliser, and all other indirect energy consumption associated with buildings, machinery and contractor services.

FarmGHG

FarmGHG is a model of carbon (C) and N flows on dairy farms (Olesen et al., 2006). The model is designed to allow quantification of direct and indirect gaseous emissions of CH_4 and N_2O from dairy farms, so that the model can be used for assessment of mitigation measures and strategies. The pre-chain emissions included in the model comprise use of energy, fertilisers, pesticides and feedstuffs. However, energy costs associated with farm buildings and machinery is not included. The imports, exports and flows of all products through the internal chains on the farm are modelled. The model thus allows assessments of emissions from the production unit and all pre-chains. The model includes N balance, and allows calculation of environmental effect balances for greenhouse gas emissions (CO_2, CH_4 and N_2O) and eutrophication (nitrate and NH_3). The model includes not only the farm gate budget components (input/output), but also the internal flows in the system. These internal flows are represented as flows between compartments in the farm system. The model also explicitly includes all C and N losses except for soil respiration and N_2 emissions from soils. The energy use is calculated for each compartment and is converted to pre-chain emissions of CO_2 and other greenhouse gases.

Milk production and herd size are given from the description of the farms. The imports of C and N in fertiliser, bedding, feed, seed and irrigation resulted from the desired milk production, and from the specification of farms, but are distributed between the model compartments in the simulations.

This results in an export of C and N in milk and meat. The farms are assumed to be operated by best management, and not to export manure. Net crop production that is not used for feed is either exported or added to the farm manure storage.

The model uses a basic time step of one month for inputs and outputs. However, in order to properly reflect the flows and emissions and the effects of management changes that operate at sub-monthly scale, daily time steps are used to simulate the flows between the animals, house and manure storage compartments. The model includes a particular manure management component, which also allows the effects of anaerobic digestion to be estimated (Weiske et al., 2006).

The model allows different methodologies for emissions estimations to be used. The tier 1 and tier 2 methodologies of the IPCC (1997) and the IPCC Good Practice Guidance (IPCC, 2000) were implemented. In addition, a default FarmGHG methodology can be used to estimate flows and emissions of CH_4 and N_2O.

SIMS_{DAIRY}

Sustainable and Integrated Management Systems for Dairy Production ($\text{SIMS}_{\text{DAIRY}}$) is a modelling framework which integrates existing models for N flows, transformations and losses (NGAUGE: Brown et al., 2005; NARSES: Webb and Misselbrook, 2004), P losses and farm economics equations to simulate NH_3 losses from manure application (Chambers et al., 1999), predict CH_4 losses (Chadwick and Pain, 1997; Giger-Reverdin et al., 2003) and cows' nutrient requirements. $\text{SIMS}_{\text{DAIRY}}$ scope focus on strategic and tactical management levels and is capable of optimising dairy management factors in order to find more sustainable systems (del Prado and Scholefield, 2006).

SIMSDAIRY operates at the farm level. Although pre-chain emissions are not implicitly included, SIMSDAIRY produces a qualitative index that accounts for the amount of bought-in manufactured fertiliser and concentrates. The model is very sensitive not only to management but also weather, topography and soil characteristics and is capable of optimising farm management practices to meet user multi-weighted criteria and to explore the possible impact of application of mitigation options on (i) pollutants such as: N_2O, CH_4, NH_3, NO_x, NO_3 and P; (ii) economic profitability; (iii) milk quality; (iv) biodiversity; (v) landscape; (vi) soil quality and (vii) animal welfare.

The effect of management practices on N, P and CH_4 losses are predicted within different components and through different processes in the soil-plant-animal system using a monthly time-step. These practices can be defined in terms of management for instance of manure, mineral fertiliser, animal and forage production.

The simulation of farm GHG losses includes those emissions from the soil (as N_2O), from animal excreta as manure or urine and dung deposited during grazing (as N_2O and CH_4) and those emissions from the rumen (as CH_4). Nitrous oxide losses from soil are simulated to occur through denitrification and nitrification processes (Brown et al., 2005). Losses from N_2O of total ammonium nitrogen (TAN) in manure N are according to different emission factors (Efs) for different manure management stages and managements according to Chambers et al. (1999), Webb and Misselbrook (2004) and Webb et al. (2006).

FarmSim

FARMSIM (for FARM SIMulation) is a model of greenhouse gas emissions at the livestock farm scale, structured into 9 interacting modules (Saletes et al., 2004). FARMSIM includes imports, exports and internal flows of products between the different components of the farm system. FARMSIM includes the PASIM model (Vuichard et al., 2007) for the greenhouse gases exchanged over the different grassland types on the farm and integrates the IPCC methodology Tier 1 and Tier 2 (IPCC, 1997) for the CH_4 and N_2O emissions coming from croplands and cattle housing. FARMSIM uses detailed data inputs concerning the farm structure (area and type of crops and of grasslands, herd types), the herd (number of animals per type each fortnight), the grasslands (grazing and cutting dates, stocking rates, organic and inorganic fertiliser applications), the crops and the feeding and waste management systems. From these data, FARMSIM calculates inputs needed to run the pasture simulation model PASIM) for each of the grassland plot in the farm. The PASIM model allows tosimulate the average net annual balance of greenhouse gases (CO_2, N_2O, CH_4) exchanged by the managed grassland plots. Other outputs from FARMSIM are used to estimate CH_4 and CO_2 emissions in the cowshed, according to liveweight, feed composition and level of feed intake, and CH_4 and N_2O emissions from the manure management using the IPCC methodology – Tier 2.

The PASIM model is driven by hourly or daily weather data for temperature, precipitation, vapour pressure, radiation, and wind speed. Site-specific model parameters include the N-input from mineral and/or organic fertilisers and atmospheric deposition, the fractional clover content of the grass/clover-mixture, the depth of the main rooting zone, and some other soil physical parameters. The model is fully dynamic and is used to simulate above- and below-ground dry matter production of a perennial sward in relationship to fluxes of C, N, water, and energy. PASIM can be used for either grazing or cutting. The animal submodel calculates intake by cattle, milk and meat production, and losses of CO_2 via respiration and CH_4 by enteric fermentation at the grazed grassland level. The production and transport of the main inputs were accounted for into the input fluxes category, which includes fuel, electricity, N-fertilisers and feedstuffs. The data for production and transport of inputs were based on a full accounting scheme as used in Life Cycle Analysis.

FASSET

The FASSET whole farm model simulates carbon and nitrogen fluxes from whole farms (Berntsen et al., 2003). The model links flows between fields (crops), feed storages, livestock and manure storages. All flows and processes are simulated on a daily basis. The model simulates emissions of NO_3, NH_3, N_2O, N_2, CH_4 and net flux of CO_2.

FASSET consists of an optional economic optimisation model and a deterministic, dynamic simulation model with a daily time step, sharing general principles regarding soil/crop interactions with many plots scale simulation models. The emphasis is on flows of nitrogen and carbon throughout the farm system, including turnover of soil organic matter, plant uptake, denitrification, N_2O emissions, nitrate leaching, animal intake and ammonia loss. The model can simulate variable types and numbers of animals, animal housing and manure storage, crops and soils. Since the largest N surpluses are associated with intensive livestock farming, far more attention is paid to the transformations of animal manure than in other farm models.

Currently the FASSET model can simulate whole crop rotations with the both arable crops and grasslands (e.g. winter wheat, spring wheat, winter barley, spring barley, fodder beets, winter rape, peas, maize, potato, grass and clover) (Olesen et al., 2002). The model also facilitates simulation of competition and coexistence between plant species, which makes it possible to simulate crops like grass/clover leys, barley/pea mixture, and undersown crops (Berntsen et al., 2004). The crop/soil model has also been extended with the capabilities to simulate urine and dung patches on grazed grass/clover fields (Hutchings et al., 2006).

The FASSET model allows both cattle and pig systems to be simulated, and it distinguishes between various age groups in the simulations (Berntsen et al., 2003; Hutchings et al., 2006). The model estimates the production of meat and milk and partitions the remaining nutrients into urine and faeces. The cattle model handles both housed and grazing systems (Hutchings et al., 2006). The manure flow and associated ammonia emissions are handled according to Hutchings et al. (1996).

The pig module describes the flow of C and N through sows, piglets and finishing pigs (Berntsen et al., 2006). The module assumes that production is homogenous over a year i.e. is a continuous rather than a batch process. Both the feed ration and animal growth are inputs. The cattle module describes the flow of C and N through dairy and suckler cows, calves, heifers and bull calves. The feed ration, including grazed feed, is input and the animal growth and milk production are simulated on the basis of the energy and protein provided in the feed.

The animal housing module simulates the flow of C and N through the housing and the losses as CO_2, CH_4, N_2, NH_3 and N_2O that occur. The module contains one or more animal section modules, each of which itself can contain one or more floor types. The ventilation rate and inside temperature are simulated dynamically. Similarly, the manure storage module simulates the flow of C and N through slurry stores or manure heaps and the losses as CO_2, CH_4, N_2, NH_3 and N_2O. The emission of NH_3 from housing and storage is simulated dynamically whereas the losses of other gasses are simulated using emission factors.

The operations manager contains a grazing manager that manages the grazable fields by simulating the length of growth periods, the number of fields to be grazed and the timing of the harvesting of roughage crops to make winter feed. The cattle feeding manager adjusts the feed ration to compensate for weather-induced variations in the availability of grazable feed.

FYNE

The FYNE model is a N mass flow model that estimates NH_3 losses to the atmosphere. The model traces the flow of nitrogen from the initial excretion by animals to the storage of the slurries and manures removed from the livestock housing and simulates NH_3 losses to the atmosphere using an emission factor approach. The emission factors have been based on the data from the UK Defra-funded project ‘NARSES’ (National Ammonia Reduction Strategies Evaluation Systems) (Webb et al., 2002), which has modified the emission factors of Misselbrook et al. (2002) to take into account additional experimental studies. The model takes inputs of livestock type/numbers, housing type/duration, manure/slurry storage methods and the import/export of manures and slurries. The outputs of the model are the NH_3 losses to the atmosphere from livestock housing, hard standings (solid surfaces used for livestock movements) and manure/slurry stores for all common livestock types.

NGUAGE

NGUAGE is s model of nitrogen flows in grassland field systems (Scholefield et al., 1991; Brown et al., 2005). The model simulates the cycling of N in grassland systems grazed by beef cattle and predicts the annual amount of N in liveweight gain, and the amounts lost through ammonia volatilization, denitrification and leaching, on the basis of fertilizer application and soil and site characteristics.

The model has been constructed from the average annual amounts of N passing through various components of the N cycle in ten field systems grazed by beef cattle. The amounts were either measured directly or were calculated from empirical sub-models, assuming a balance between inputs to, and outputs from the soil inorganic N pool. The model is given wide applicability through the inclusion of a mineralization sub-model which is sensitive to soil texture, sward age, previous cropping history, and climatic zone. Another important sub-model determines the partitioning of soil inorganic N to either plant uptake or the process of loss: the proportion partitioned to plant uptake decreases as the total amount of soil inorganic N increases.

Table 1. Farm model characteristics.

Model	Farm components	Emissions	Management	Time step	Code
DairyWise	Cattle, feed, manure, fields	NO_3, NH_3, N_2O, CH_4, CO_2	Yes	Monthly ?	?
FarmGHG	Cattle, feed, manure, fields	NO_3, NH_3, N_2O, CH_4, CO_2	Yes (partly)	Monthly	Delphi (available)
$SIMS_{DAIRY}$	Cattle, manure, fields	NO_3, NH_3, N_2O, NO_x, CH_4, CO_2	Yes (?)	Monthly (?)	?
FarmSim	Cattle, manure, fields (grassland)	NO_3, NH_3, N_2O, NO_x, CH_4, CO_2	No	Daily (monthly)	Excel, C++
FASSET	Cattle, pigs, feed, manure, fields	NO_3, NH_3, N_2O, N_2, CH_4, CO_2	Yes	Daily	C++ (available)
FYNE	Manure	NH_3	No	Monthly (?)	?
NGUAGE	Cattle, grassland	NO_3, NH_3, N_2O, N_2, NO	No	Monthly	Delphi

Recommendations

There are a number of farm scale models described in literature, and most of these are probably available for application in NitroScape. However, only a subset of these models consider all the necessary farm compartments, and most of the models only consider cattle-based system. FASSET is the only model, which allows both cattle and pigs to be simulated.

Since the plot scale models in NitroScape probably will be running at daily scale, it is preferable also to have the farm scale model operate at this time scale. Only the FASSET model has incorporated a daily timescale for all model components.

However, not even the FASSET model incorporates all the components needed. It will thus be necessary to include more livestock types in the model. Since the FASSET model is developed and maintained by one the NitroEurope C4 partners, this should be possible with a minor effort. It is therefore proposed that the Farm scale model in NitroScape is based on FASSET.

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