Evaluation of greenhouse gas emissions and design of mitigation options: a whole farm approach based on farm management data and mechanistic models

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Abstract: *Agricultural activities are important sources of atmospheric nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). In the European Union, the agricultural sector contributes approximately 10% of the total emitted greenhouse gases (GhG). We search for evaluating GhG emissions at the farm level and desiging mitigation options from a biotechnical point of view. As GhG emissions occur at several stages within the farm operation, it is essential to combine nutrient cycling and farm working through an integrated farm approach to reach a full accounting of processes. Our proposal comprises the following characteristics:*

- Our whole farm approach (FarmSim) combines empirical and mechanistic modelling through describing of above and below ground C and N fluxes ; with respect to GhG, emissions can be also calculated with emissions factors, comparable to the IPCC methodology when no model is available yet as for manure management for instance.

- Rebuilding farmers' practices description from available data (on farm and through farms'network databases) needs to choose a level of information to translate real situations to generic ones. It requires thus to choose a set of farm components and compatible spatio-temporal scales in respect with the data needed by the models.

- At the moment, we coupled two models allowing to quantify the emissions of the different land uses (in our case PaSim, a grassland ecosystem model and CERES-EGC, a crop model).

- The system boundaries are limited to the farm gate, or may include pre- and post-chain effects according to more and less high inputs and the difficulty to forecast produce fate if databases are available.

- Building plausible scenarios requires to control a set of farm operation coherences to account for standing mitigation options.

In a first step, we used a case study formalized by the French Livestock Institute (IE) and some farm working data from an experimental dairy farm belonging to the French Institute for Agricultural Research (INRA), both located in semi-continental conditions (Mirecourt - North-Eastern France). The simulated farming system is a mixed dairy and crops system so as to account for a rather generic farming system.

Keywords: *greenhouse gas emissions, farm management practices, mixed crop livestock systems, modelling, whole farm approach*

Introduction

Agricultural activities are important sources of atmospheric nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2). In the European Union, the sector Agriculture contributes 9% to total EU-15 greenhouse gas (GhG) emissions, making it the second largest sector after the sector Energy. The most important GhGs from sector Agriculture are N_2O and CH_4 accounting for 5% and 4% of the total GhG emissions respectively (EEA, 2007).

The emissions from this sector decreased by 11% from 434 Tg in 1990 to 386 Tg in 2005. Large reductions occurred in the largest key sources CH_4 from Cattle and N_2O from Direct Soil Emissions. The main reasons are the declining cattle numbers and a decreasing use of fertiliser and manure in most Member States rather than specific GhG policies. With Indirect Emissions (N_2O), this three key sources account for about 70% of agricultural GhG emissions of the EU-15 (EEA, 2007).

In contrast to industry, the emissions from agriculture are not confined to relatively few large emitters, but are diffusely spread across Europe. On each individual farm, the farmer is responsible for the actions taken to work its farming system. As farmers' goals may be rather different considering historic and geographical conditions, farmer practices are themselves more or less different and frequently require an individual approach, especially to assess and eventually change the farm system working.

Research has focused on identifying the sources, studying the biotic and abiotic processes (Freibauer, 2003 ; Soussana et al., 2007) and reviewing mitigation options either to reduce GhG emissions (Weiske et al., 2006) or to sequester carbon in the soil (Soussana et al., 2004; Smith, 2004).

Since agricultural management is one of the key drivers of C-sequestration and emission, but also of limiting N_2O and CH_4 emissions from grassland, cropland and animal production, there is potential to reduce the net GhG balance. However, management choices may lead to major trade-offs between processes, especially when you consider mixed farming systems combining crop and animal production as in many European ruminant livestock systems. Moreover, the structure of the GhG reporting framework (IPCC, 1997) did not stimulate an integrated approach at the farm level. Since management decisions are really made at the farm level, the assessment of emissions and the design of mitigation options have to be done through a farm level full accounting approach, including farmer's practices.

Some proposals exist about the farm level approach for mitigating GhG emissions from ruminant livestock systems: Schils et al. (2006a) proposed a general framework considering the definition of two essential farm compartments, through the utilisation of homegrown roughage by animals in one hand and the return of excreta to the soil-crop system in the other one. The development of whole farm approaches has been taken up by several other research groups in Europe, and some models were used to this end as DairyWise (van Alem and Van Scheppingen, 1994 ; Schils et al., 2005), FarmGHG (Olesen et al., 2006) and $SIMS_{DAIRY}$ (del Prado et al., 2006). In New-Zealand, a proposal was made to use the OVERSEER® nutrient budget model to estimate on-farm GhG emissions (Wheeler et al., 2007). For our own purpose, we seek for using another model, FarmSim (Salètes et al., 2004) initiated some years ago during an European research project (GREENGRASS, EVK2-CT2001-00105).

This paper presents some recent advances got by our research group, extending the previous characteristics of FarmSim model through a best accounting of croplands emissions. So, we will outline the main principles of our approach; then the characteristics of the mixed crop livestock farm on which the model was setup before coming on the working of the model and first results delivered. A discussion will follow on including the perspectives we have to improve FarmSim model.

Model description

A whole farm approach

A crop livestock farm is simultaneously a management unit where decisions are making to implement practices and a production unit where fields, animals, buildings, machinery and stores contribute to its environmental balance generating energy and matter flows including GhG. These flows are closely interconnected and their coherence can only be understood at the farm level.

The emissions of GhG are related to carbon and nitrogen flows and environmental conditions. Here, we will consider carbon and nitrogen cycling through a whole farm system approach (Figure 1) in order to quantify and assess the main processes that lead to GhG release or uptake by the farm and to simulate the resulting farm GHG balance.

The interactions between the different flows are especially strong in the mixed crop livestock farms with ruminants: a large part of effluents are recycling on the fields to contribute to homegrown fodder, feeds and straw 'supply for animals' bedding. Moreover the farm working needs the purchase of a variety of inputs (fertilizers, feedstuffs, electricity and fuel…), the production and transport of which having needed energy and produced GhG too. Balances at the farm level extended to the purchased inputs are therefore relevant at the same time as diagnosis and decision making tool and to depict the flows relationship. However, such an accounting for requires information about prechains.
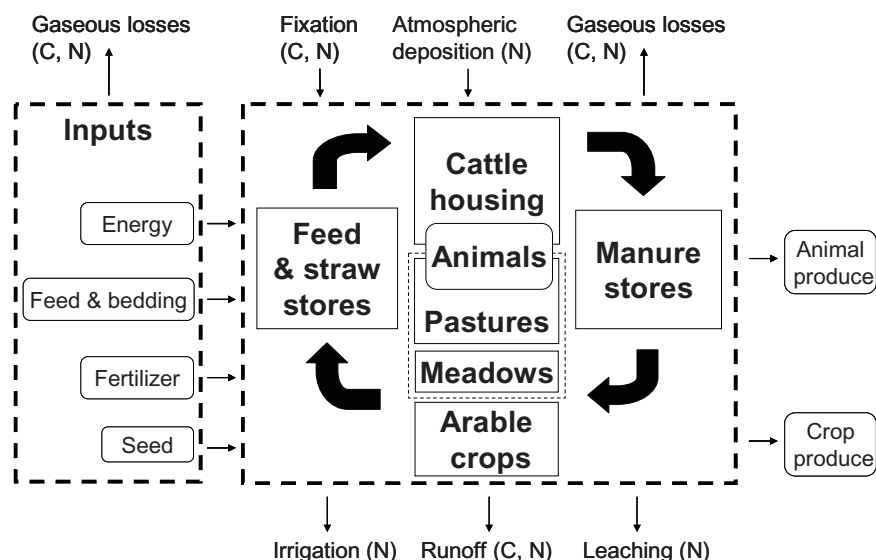
Figure 1. Carbon (C) and nitrogen (N) flows from a whole mixed crop livestock farm approach

A semi-mechanistic model

FarmSim has been first designed to describe the above and below ground C and N fluxes in cattle farms, and calculate the net balance of GhG emissions (Salètes et al., 2004) through a consistent description of the farm features and practices both including grazing animals.

In the first release, it only involved a strong connection to the Pasture Simulation model PaSim, the grassland model originated from the Hurley Pasture model (Thornley, 1998) to simulate grasslands emissions. All the other emissions were calculated using IPCC methodology (Tier 2) with emission factors.

PaSim is a model operating at the field scale originally developed to simulate dry matter production and associated flows of carbon, nitrogen and water in productive pastures (Riedo *et al.*, 1998, 2000). It was extended by Schmid *et al.* (2001) with respect to the production and diffusion of N_2O, then by Vuichard *et al.* (2007) concerning water stress, senescence, detrimental impact of trampling and excreta by grazing animals on vegetation and effects of diet quality on the emissions of methane from grazing animals. Its target ecosystem is essentially a mixed sward, with grasses and legumes co-existing in fixed proportions. PaSim calculates the growth and senescence of aboveground vegetation biomass accounting for sporadic removals when the grassland is cut and for continuous removals when it is grazed. Limitations induced by high leaf area index (LAI), soil water deficits and aging of leaves are also included. This model allowed to get a fully dynamic calculation of fluxes of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) in the grasslands.

FarmSim model is a simulation framework allowing to describe in a consistent way the characteristics of a mixed crop ruminant farm and to calculate the inherent emissions. The model is structured into 9 modules (Figure 2), requiring detailed data inputs on the farm structure, meteorological conditions, soils, animals, grassland and cropland management, but also animal winterfeeding strategy, waste production system and imported resources.

Whilst GhG emissions from grasslands are always calculated by PaSim model, the emissions from croplands are now calculated by the CERES-EGC model: This latter model is based on CERES (Jones and Kiniry, 1986), a mechanistic fully dynamic model modified to suit French conditions (Gabrielle et al., 1998). CERES simulates the dynamic of water, carbon and nitrogen in soil-crop systems. It runs on a daily time step and is available for a large range of crop species. It runs from standard weather data. CERES comprises three main sub-models. First, a physical module simulates the transfer of heat, water and nitrate down the soil profile, as well as soil evaporation, plant water uptake and transpiration in relation to climatic demand. Next, a microbiological module simulates the turnover of organic matter in the plough layer, involving both mineralization and immobilization of inorganic N. In CERES-EGC, the NCSOIL model (Molina et al., 1983) was substituted for the original CERES module, and comprises three endogenous soil OM pools: microbial biomass, active humus

('humads') and passive humus. The third module simulates crop growth and development. Photosynthates are partitioned on a daily basis to currently growing organs (roots, leaves, stems, fruits) according to crop development stage. The latter is driven by the accumulation of growing degree days, as well as cold temperature and day-length for crops sensitive to vernalization and photoperiod. Crop N uptake is computed through a supply/demand scheme, with soil supply depending on soil nitrate and ammonium concentrations and root length density.
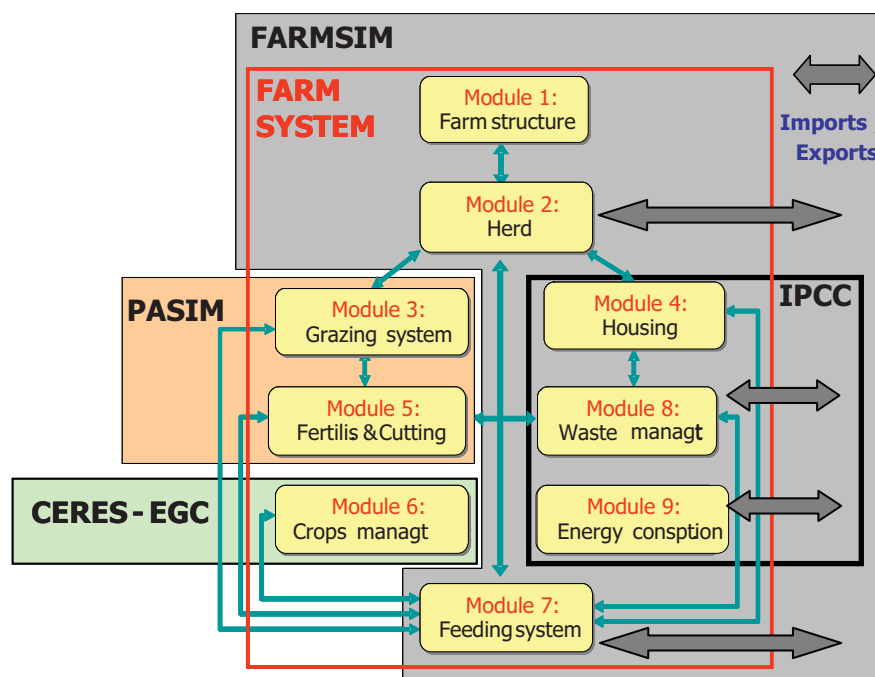

Figure 2. Structure of FarmSim coupled with crop and grassland dynamic models

From farmer's practices to modelling data

Coupling with PaSim and CERES-EGC allows to account for mixed crop livestock farming systems with a special attention to management regime implemented on grassland and cropland plots. So, the main step of model inputs relies on a translation of farmer's practices into models' variables.

Consequently, for each grassland plot, information is required about time, nature and intensity of removed grass, through indications of cutting or grazing regime, and thus grass yield or stocking density. In addition, N fertilizer supply both through mineral and organic fertilizer applications is needed in regard with spreading time and rate. Moreover, different grassland types may be distinguished, first from a bio-geographical point of view, and secondly from the species composition and management regime they have: even PaSim model is not yet able to simulate such a range, we use it through different runs to describe in a best way semi-natural permanent grasslands, intensively managed permanent grasslands, recently sown grass-clover swards, and even unimproved rough grasslands.

For croplands, the required data to describe the different crops involved in the farm cropping system rely on the plant variety and the following practices' data: seeding time and density, time and rate of nitrogen supply through mineral and organic fertilizer applications, harvesting time and crop residues fate. Today, no detail can be accounted for tillage yet.

At the moment, no animal production model is coupled with PaSim and CERES. The emissions associated with animal winterfeeding, livestock housing and manure storage, stay calculated using a spreadsheet module, according to IPCC methodology. In the same way, direct and indirect energy use and emissions associated with the production and providing of imported resources (including transport to the farm) are also accounted for on a special spreadsheet gathering data about fuel, electricity, fertilizers, veterinary products and pesticides, concentrate and others supplies purchased for the farm production. Different databases may be used for these calculations, at the user's convenience.

This farm description relies on different likelihood checking, as about fodder and homegrown feeds harvesting collated to animal intake, about collected, stored and spread manure, but also about herd management and batching practices for instance. According to the farm description, one of the main difficulty consists in grassland's analyse to account for the farm operating from a realistic point of view. To this end, we use operational field management calendars (Figure 3) from which we identify different grassland types according to their management, collating fertilizer applications, grass removal regimes (grazing or cutting) and for grazing, animal types and stocking density.
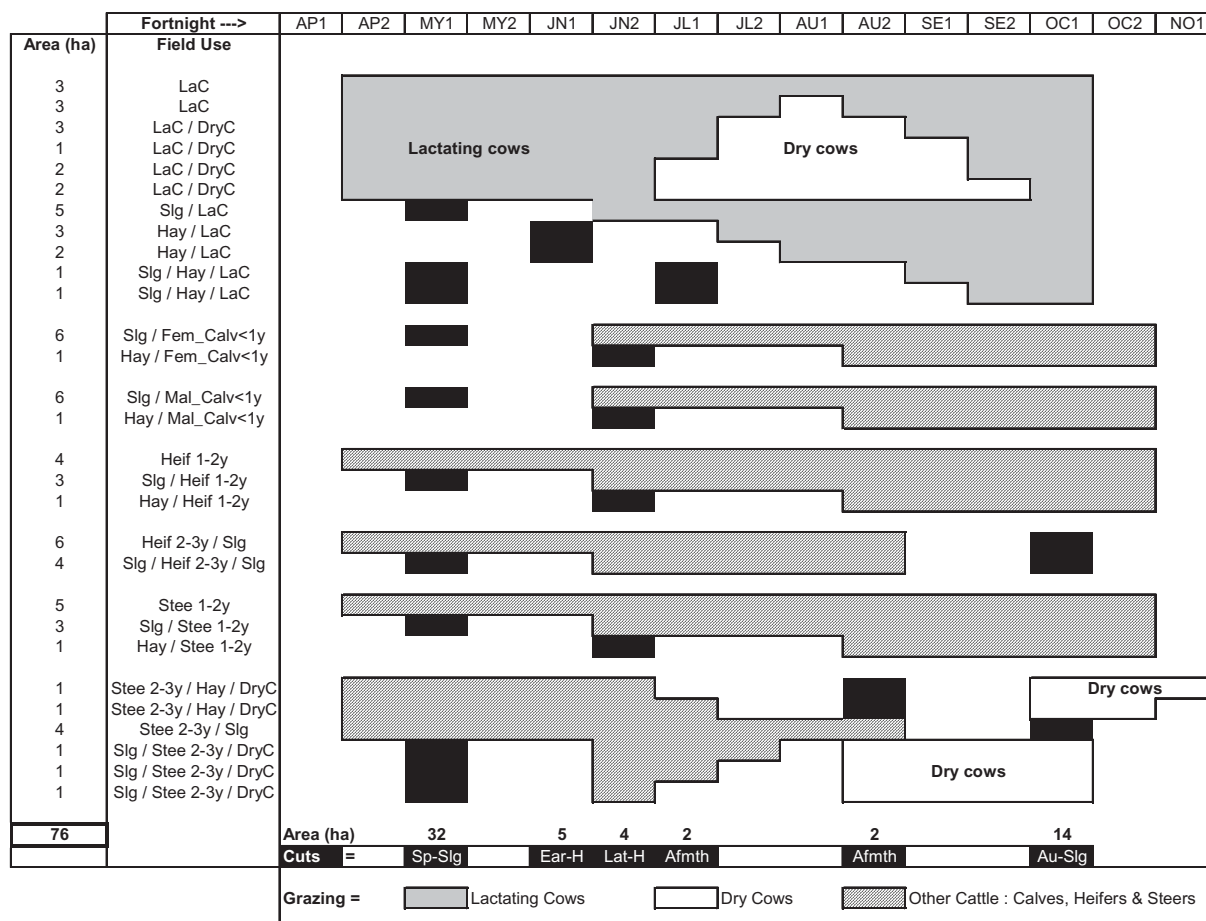
Area (ha)	Field Use
3	LaC
3	LaC
3	LaC / DryC
1	LaC / DryC
2	LaC / DryC
2	LaC / DryC
5	Slg / LaC
3	Hay / LaC
2	Hay / LaC
1	Slg / Hay / LaC
1	Slg / Hay / LaC
6	Slg / Fem_Calv<1y
1	Hay / Fem_Calv<1y
6	Slg / Mal_Calv<1y
1	Hay / Mal_Calv<1y
4	Heif 1-2y
3	Slg / Heif 1-2y
1	Hay / Heif 1-2y
6	Heif 2-3y / Slg
4	Slg / Heif 2-3y / Slg
5	Stee 1-2y
3	Slg / Stee 1-2y
1	Hay / Stee 1-2y
1	Stee 2-3y / Hay / DryC
1	Stee 2-3y / Hay / DryC
4	Stee 2-3y / Slg
1	Slg / Stee 2-3y / DryC
1	Slg / Stee 2-3y / DryC
1	Slg / Stee 2-3y / DryC
76	

Fortnight --->: AP1, AP2, MY1, MY2, JN1, JN2, JL1, JL2, AU1, AU2, SE1, SE2, OC1, OC2, NO1

Lactating cows — Dry cows — Dry cows

Area (ha)	32	5	4	2	2	14
Cuts =	Sp-Slg	Ear-H	Lat-H Afmth		Afmth	Au-Slg

Grazing =   ▢ Lactating Cows   ▢ Dry Cows   ▨ Other Cattle : Calves, Heifers & Steers

Figure 3. Grazing and cutting calendar of the grassland fields of a mixed crop livestock farm (Mirecourt farm)

The above operational calendar allowed to distinguish four main grasslands' types: (i) permanent intensive grasslands exclusively grazed by cows (14 ha), (ii) permanent intensive grasslands harvested and grazed by the different animal batches (26 ha), (iii) semi-improved grasslands exclusively grazed by heifers and steers (9 ha) and (iv) semi-improved grasslands harvested and grazed by different animal batches (27 ha), with specific mineral and organic fertilisation practices.

Case Study

Mirecourt Farm

The FarmSim new release has been performed for a mixed crop livestock farm located in Lorraine, North-East of France. As a matter of fact, this study case is an ideal type built by the French Livestock Institute, resulting from many real monitored farms and thoroughly informed with data from an INRA experimental farm located in Mirecourt.

Farm structure relies on an agricultural area of 100 ha with a milk quota of 300,000 liters produced by a 48 cow dairy herd. In addition, steers are kept from this dairy herd. Permanent pasture is the major

land use with 76 ha. In addition, 24 ha are cultivated with a maize-wheat rotation (including 3 ha of fallow land). Grasslands are grazed from mid April to late October or only during a part of this period: thus 32 ha are harvested as spring grass silage in mid May and 9 ha as hay in June. In addition, some pastures are cut as aftermath during summer or as grass silage in autumn. Mineral nitrogen (N) is supplied from early March to mid summer for most of grazed and cut grasslands. Intensive (40 ha) and semi-improved (36 ha) permanent grasslands are spread on average with 110 and 45 kg N ha^{-1}, respectively. In addition, the intensive grasslands receive 12 tons long term stored manure per ha (i.e. 70 kg N ha^{-1}) during autumn. Other grassland types get by mean 60 kg N ha^{-1} from fresh manure in winter. The grasslands yield from 4.5 to 6.5 t. Dry Matter (DM) ha^{-1} yr^{-1} and total roughage stores of about 100, 33 and 7 t. DM as grass silage, hay and aftermath respectively.

The maize crop yields about 120 t. DM as silage used for dairy cows diet from October to April. The winter wheat crop provides about 20 t. DM home-grown feed, and a third (about 35 t. DM) of the straw needs for both heifer's feeding and cattle bedding. Wheat and maize crops are fertilised with 15 tons composted manure, 22 tons fresh manure and 110 and 75 kg mineral N ha^{-1}, respectively.

The dairy herd consists in 48 Prim'Holstein cows producing about 6700 kg milk per year. The replacement rate is 35% and the heifers calve at 36 months of age. The calving dates run from August to November. All male calves are kept as 3 years old steers. The feeding system relies on grass utilization except for indoor lactating cows. From October to April, dairy cows are fed with maize silage (13 kg DM cow^{-1}d^{-1}) and a little hay and aftermath (2 kg DM cow^{-1} d^{-1}) as roughage, supplemented by purchased soya-bean cakes and homegrown flattened wheat (2.2 kg DM cow^{-1} d^{-1} of each) as concentrates. During all the grazing period (six to seven months long), the cows produce milk from grass exclusively. First year calves eat a little hay first, then grass silage and hay just before to be turned out in June. During the grazing period calves intake about 0.5 kg DM hay per day. They are back to stable in late October, simultaneously with heifers and steers which are then supplied with 4.5 and 3 kg DM animal^{-1} d^{-1} grass silage and straw, respectively. Steers are fattened at grazing and sold from June to September. Roughage balance of this crop livestock farm is rather tense with a global stocking rate of 1.4 Livestock Unit (LU) ha^{-1} relying on 13% maize crop, 46% intensive grasslands and 41% semi-intensive ones.

A mitigation package for Mirecourt Farm has been conceived through a rather strong extensification associated with a feeding self-sufficiency request. This strategy relies on three main options: (i) a strong nitrogen fertilisation reduction (-50%) associated with an important decrease of stocking rate to 0.9 LU ha^{-1} assuming an increase of white clover in pasture composition, (ii) a complete change of the cropping system (from maize-wheat to field bean-triticale-barley crop rotation) allowing a self-sufficiency for concentrate supplementing hay and grass silage diet, and (iii) a giving up of steer production (-36 LU) associated with an increase of the cows productive lifetime to keep less heifers (-10 LU). All these options result in a slight decrease of milk yield from 6800 to 6400 Kg cow^{-1} y^{-1}.

First simulation results

Global budgets of GhG emissions (expressed as t.CO2 ha^{-1} of Used agricultural Area (UA)) are presented broken down into two components: the net internal fluxes and the inputs related fluxes. The Global Warming Potential (GWP) of Mirecourt Farm firstly results from animal respiration (CO$_2$) and enteric fermentation (CH$_4$) emissions, the latter being 60% of respiration. These two emissions are directly suited to the cattle number and consequently, a strong animal number decrease results in an important reduction of these components after mitigation: nevertheless, they stay the most important emissions, standing up to 85% of internal fluxes and 76% of the total emissions. Before mitigation, N$_2$O emissions from grassland fertilization fill in the third place (15% of internal fluxes), but the strong reduction of mineral nitrogen makes it far away into the internal fluxes after mitigation.

Considering together internal and external fluxes associated with mineral N use, the total N fertilizer contribution falls down from 18 to 9% of the total calculated emissions. Fuel (direct and indirect) emissions result in the fourth component (about 6% of the total emissions), both before and after mitigation, whilst N$_2$O emissions from cropland N fertilization stay a very low component in the two situations. In addition, the self-produced concentrate supply makes the purchased feedstuff emissions disappear when they stood up to 30% of the external emissions before mitigation (but only 3% of the total emissions).
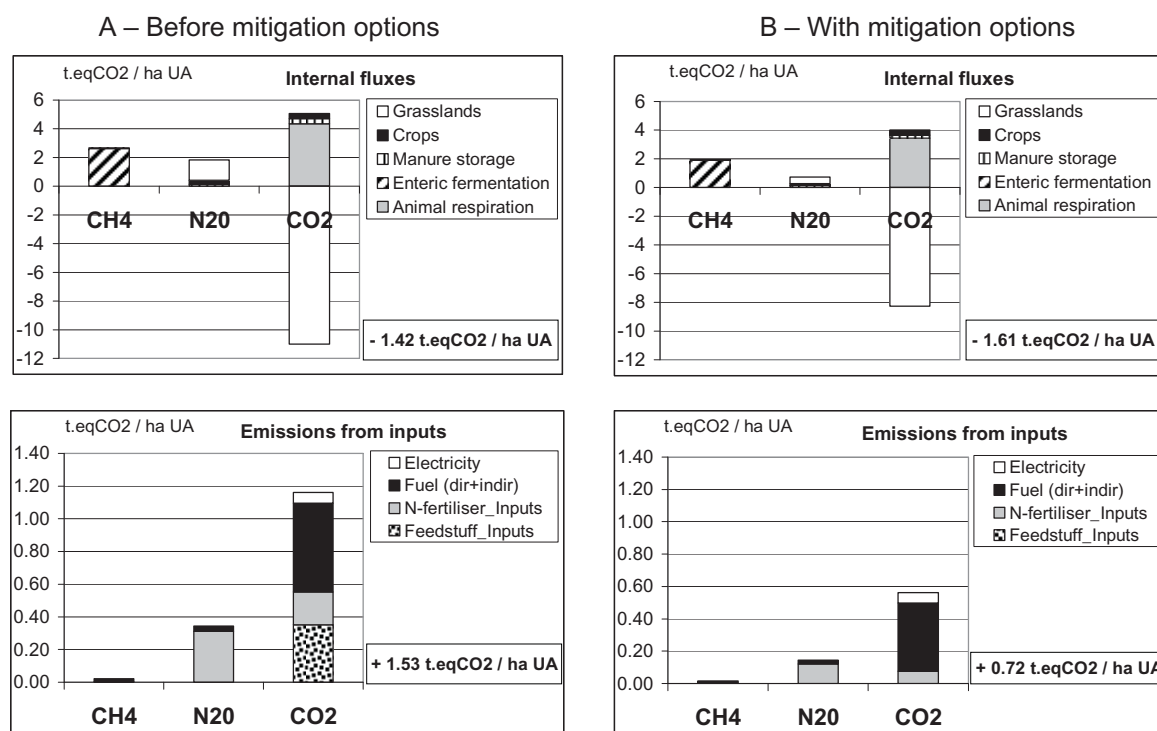
Figure 4. GhG budgets from simulated emissions before (A) and after (B) mitigation options at Mirecourt Farm

A special mention must be done about C balance and release or sequestration behaviour of grassland and cropland. At the farm scale, the current C storage rate in the soil is unknown. So, an assumption of Net Biome Productivity (NBP) was done according to literature values (Janssens *et al.,* 2003; Soussana *et al.,* 2004) and considering croplands as moderate sources (+ 0.46 t.C-CO_2 ha^{-1} y^{-1}) and grasslands as moderate sinks (- 0.335 t.C-CO_2 ha^{-1} y^{-1}). So, these two fluxes are calculated in addition with the other ones, making the farm become a net sink (- 0.89 t.eqCO_2 ha^{-1} y^{-1}) despite of a sequestration decrease after mitigation.

Discussion and perspectives

The whole farm approach is a powerful tool to assess the impact of agricultural practices, even in such complex situations as crop livestock farms. We have demonstrate that a full GhG accounting approach can be developed for these farms and that it allows to estimate consistently GhG budgets, including pre-chain emissions. Considering the pre-chains is clearly important to give to farmers and advisers a better awareness of the consequences of their management decisions for the global environment. Importantly, by simulating the GhG budget of the grasslands with PaSim we take into account the role of seasonal and interannual variability in climate for the GhG emissions at the farm level. According to the croplands, we have now coupled the FarmSim model with CERES-EGC, a generic crop model, allowing then the simulation of field scale GhG balance more efficient than using emission factors for crops practices. This is important to calculate farm budgets over a commitment period in a more realistic way. Another point consists in the units with which the emissions are expressed: if we choose above Kg eqCO_2 ha^{-1} UA, it is then possible to use Kg eqCO_2 LU^{-1} and even Kg eqCO_2 GJ^{-1} of produce to account for milk, meat and cash crops together.

Nevertheless, this approach still has some weaknesses. First, the assumptions made with the NBP, while helpful, need to be refined by running PaSim and CERES-EGC for a range of initial soil C contents rather than from an equilibrium. Assumed soil C contents may in the future be derived from measurements in the farm or from databases on soil C that now include the land use. Second, the emission coefficients derived from the IPCC methodology can be refined at the farm scale, by making them more flexible, e.g. for the indoors emissions from litter and manure stores.

The FarmSim model is not yet so complete as it would be: an herd management model would largely welcome to help checking the relationship between forage and manure management systems. A special effort stays to be done about time considering for successive years, e.g. to account for crop sequences and climatic series. In a longer time step, taking account of the background of the fields would allow to be more explicit and consequently, it would be more efficient to consider realistic transition to mitigation options. In the same time, some practices as supplemented grazing or alternative tillage are not still well considered. Finally, parametrization stays largely to improve (first to describe soils characteristics) and model sensitivity to be tested.

Conclusion

While there are clear prospects for mitigation of the individual GhG both from grasslands and croplands, there are clear trade-offs and synergies between the different GhG (and even with other gases as ammoniac or NO_x) which are only beginning to be quantified. Increased soil carbon storage associated with increased fertiliser use can be offset by increased nitrous oxide emissions, while changes to reduce methane emissions may cause similar interactions. It is therefore important to assess potential mitigation options for their impact upon all the GhG.

FarmSim, PaSim and CERES-EGC are interesting tools to explore a large range of mitigation options starting from farming actual conditions. A full accounting framework is the only way to give a consistent assessment of the mitigation strategies at the farm scale. A bottom-up approach could induce a better awareness for stakeholders. In addition, since mitigation options have to be implemented by farmers, a farm scale model might give the required insight into the trade-offs between the different GhG despite the great heterogeneity of farming practices.

Implementation of technological measures often requires investments (manure digesters) but these may be cost-effective too in the medium term. Structural adjustments as decreasing of the animal number or changing crop sequences are expensive too and only cost-effective in terms of mitigation of GhG emissions in the longer term. But some management adjustments are probably cheaper and immediately cost-effective too, as manure management, crop management and animal feeding strategy. In this way, reducing N surpluses both at the field scale and at the farm scale allows to reduce N losses to the environment. As Schils et al. (2006b) noted it, there is certainly scope to use N surplus as a proxy for GhG.

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