MELODIE : A Whole-Farm Model To Study The Dynamics Of Nutrients In Integrated Dairy And Pig Farms

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EXTENDED ABSTRACT

In France, nutrient losses from farming systems are a source of concern for water and air quality. Due to this pressure, the production systems are quickly evolving. However, it is not clear which practises are best for the environment and should be favoured. The model MELODIE aims to evaluate the environmental impact of production strategies in integrated dairy, swine and crop farms. It is intended for use in research, not as a decision support system for farm management.

MELODIE dynamically simulates the flows of carbon, nitrogen, phosphorus, potassium, copper, zinc and water within the whole farm and over the long-term. It consists in a biophysical module interacting with a decision module. The biophysical module simulates the nutrient flows at a daily time step. It includes interconnected sub-models which simulate soil/crop, animal and manure processes. Wherever possible, existing sub-models were used, and specific modules were developed when necessary. The decision module includes a planning sub-model and an operational management sub-model. The planning sub-model is used annually to translate general objectives and constraints into a crop allocation and a manure allocation, which are translated into an activity plan for the year. This plan is applied by the operational management sub-model. Every day, the nutrient flows are calculated by the biotechnical system, and the activity plan is examined, for context-dependent application: the operations scheduled are executed only when the conditions are suitable. The plans may also be modified. For example, if a waste application has not been possible, the subsequent applications should be made at a higher application rate.

The planning module ensures the consistency between the expected animal feeding and the crops. Since the plan established is applied in a context-dependent way, MELODIE copes with the variability of climatic years. Therefore, thanks to the interactions between the biotechnical system and the decision system at different time scales, MELODIE is able to run consistently under different long-term climate series.

MELODIE upscales models developed at the field or animal scale and on short-term periods, by considering the management of the whole farm system. The goal is to study the emerging properties of the system: because of the interactions between the different parts of the farm, and the tradeoffs between different economic and/or environmental objectives, the environmental impact of a farming system may be different from what was inferred at lower scales.

Because the nutrient flows within the farm are dynamically simulated, it is possible to study both the spatial and temporal heterogeneity of the environmental risks. However, because of the quantity of data generated by the model, new challenges arise. In experimental studies, it is not possible to obtain such a quantity of data. It is thus necessary to develop new environmental indicators, adapted to this context.

As a conclusion, thanks to the association of a biotechnical model and a decision model, MELODIE enables one to perform multi-criteria evaluations of the impact of production strategies. It is a framework for virtual experimentation on animal farming systems, and could be extended to deal with other issues than nutrient flows.

1. INTRODUCTION

In regions of intensive pig and dairy farming, water quality can be threatened by nutrient losses from these farming systems. Other risks of pollution (losses to air and accumulation of nutrients in soils) are also sources of concern. Although farming systems impact their environment in many different ways, positive or negative, nutrient flows are one of the first concerns, at least in regions of high animal densities. Several dynamic models simulating farming systems exist. As far as animal farms are concerned, three dynamic mechanistic models were found: the Integrated Farm Systems Model: IFSM (Rotz and Coiner 2004), Dexcel's Whole Farm Model: WFM (Wastney *et al.* 2002) and Farm ASSEsment Tool: FASSET (Jacobsen *et al.* 1998). IFSM and WFM both deal only with dairy farms, mainly in the USA but with worldwide potential applications for the first one and mainly in New Zealand for the second one. Both models are centred on the technical and economic results of the modelled farm. IFSM performs one-year simulations, with a detailed biotechnical module. The decisions taken by the farmer are mostly model inputs. In the WFM, the decisions, like movements of the herd between paddocks, are modelled. FASSET deals with pig and dairy farms, and is more centred on the environmental impact of farming systems. It performs long term simulations (30 years), and associates a decision module and a biotechnical module. The decision module is a linear programming procedure used to plan the farm activities every year. During the year, little adaptations are made considering the state of the system, and the production plans are applied without modifications.

The objective of this work is to build a model to evaluate ex-ante the environmental impact of production strategies in pig and dairy farms. The evaluation of the environmental impact is centred on nutrient flows and the associated pollution risks. The model is intended to be applied for the main systems encountered in France. It can be used in research, to compare different strategies. The aim is not to use it directly as a decision support system for farm management.

2. DESCRIPTION OF THE MODEL

2.1. Overview

MELODIE is a model simulating nutrient flows over several decades at the farm scale, in pig and dairy farms. The nutrients taken into account are the ones whose losses are linked with environmental risks: carbon (C), nitrogen (N), phosphorus (P), potassium (K), copper (Cu) and zinc (Zn). Water (H_2O) flows are also simulated. MELODIE is based on the ontology of agricultural production systems proposed by Martin-Clouaire and Rellier (2003). Some elements of description of this ontology are given throughout the presentation of MELODIE. Only the concepts that are essential to this paper are addressed. In this ontology, a production system is composed of three subsystems: the biotechnical system (or controlled system), the decision system (or manager) and the operating system. The operating system includes the resources used to conduct activities, like labor and machinery. These resources are not taken into account in the present version of MELODIE, thus the operating system is not modeled.

The nutrient flows are calculated at a daily time step by the biotechnical system, which is a set of connected sub-models described below. Four main nutrient pools are considered (fig. 1): animals, agricultural wastes (storage and treatment), soils and crops, and feed stocks. Nutrient losses to air and water are simulated, as well as nutrient flows between and within these pools. For example, animals are grouped in batches, and the nutrient flows are calculated separately for each batch. For soils and crops, each field is represented individually. Different levels of precision are associated with the nutrients: for example, the N cycle is more detailed than the Cu or Zn flows, for which only balances between pools are calculated.

Decisions made by farmers are simulated by the decision system, which interacts with the biotechnical system throughout the simulation (fig. 1). Decisions are taken at two time scales. Every year, a planning module generates flexible plans. These plans are examined every day, for context-dependent application: the operations scheduled are made only when the conditions are suitable. The plans may also be modified if necessary. More details are given in the description of the decision system below.

The main outputs of the model are losses to the environment of different nutrients, calculated daily over decades for each animal class, field or waste storage unit. These outputs can be used to calculate indicators of environmental impact, such as those used in Life Cycle Analysis (LCA).

2.2. The biotechnical system

MELODIE uses existing models wherever possible. For every process covered, the existing models or equations were studied, and the most appropriate were chosen. When no suitable model was found, new models were developed. For soils and crops, MELODIE uses STICS, a model developed by Brisson *et al.* (2003). It dynamically simulates the flows of N, organic matter (i.e. C) and water, as well as crop growth and development. STICS has been parameterised for a wide range of crops by different authors. A specific module is under development for phosphorus, so as to adequately represent the risks of runoff losses, especially after waste applications. For the other nutrients, only balances are calculated, based on the waste nutrient content (calculated within the wastes sub-model) and on the quantities of nutrient harvested. For dairy cows and heifers, the model GEDEMO (Coquil *et al*. 2005) dynamically simulates the demography of the herd, i.e. the size of 21 animal classes. The nutrient flows are calculated for each of these classes, by the model of Maxin (2006), which describes the nutrient balances of dairy cattle using easily available data. Feed intakes are calculated using the equations of the INRA system (INRA 2007). For pigs, the demography model is based on practical references and expert knowledge, and is connected with the animal housing system. The equations used for growth, feed intake and nutrient excretion are the same as in Dourmad *et al.* (2002). For the storage and treatment of animal wastes, a specific module was built from a set of existing empirical equations and emission factors. These were found in the literature, or are based on expert knowledge. The module calculates the evolution of the wastes and the losses to the air, from the excretion to the application, for the main animal housing systems and storage facilities encountered in France. The treatment of wastes by different systems (biological treatment, composting …), in order to reduce their nutrient load, is also included.

2.3. The decision system

The role of the decision system is to dynamically determine what operations should be applied to the biotechnical system. The decision-making and ensuing execution of actions are responsive to the state of the whole system and its environment. The decision-making process underlying the decision system operates on the farmer's management strategy. The ontology of agricultural production systems (Martin-Clouaire and Rellier 2003), on which MELODIE is based, provides a consistent framework to describe explicitly such a strategy. In this ontology, a strategy is composed of a plan of activities to apply to the biotechnical system and rules to apply and adapt this plan when particular events occur. The activity plan is a set of activities organized by different temporal or programmatic operators that indicate how the plan should unfold. When decisional events occur (every day, in MELODIE), the activity plan is examined. The suitable activities are extracted and become candidate for execution. The activities can be executed only if a set of conditions on the state of the system are met. For example, for crop management, harvest is possible only when the crop has reached maturity and climatic conditions are appropriate. If necessary, the activity plan can be modified in the course of the events. In MELODIE, for example if a waste application has not been possible during its time window, then the subsequent applications (on other fields) are made at a higher application rate, in order to dispose of the whole quantity of waste.

Within MELODIE, the activity plan is automatically generated. The simulation user must provide a kind of feeding road map for the animals, i.e. the feed (type and amount) to be provided, for different periods of the year and for different groups of animals. The feeding activities required to apply this road map are automatically built, as well as the activities related with the movements of animals and waste management within the buildings. For the crops, a planning module is used every year (fig. 2). The feeding road map induces the total quantities of the feed required each year, and the total quantities and composition of wastes that will be produced. These elements are used by the model TOURNESOL (Garcia *et al.* 2005), which is a cropping plan generator. It considers the feed and straw requirements and applies agronomic knowledge (potential of the fields and effects of crop sequences) to generate a cropping plan that best satisfies the goals and priorities defined by the model user. These are represented by a set of shadow prices associated with the products of the different crops. For each product, two prices are set. One is associated with the production of one unit in excess relative to the quantity needed (which can be 0, for cash crops), and the other is associated with the lack of one unit. These prices represent the priorities of the farmer because they are set independently of market prices and according to the factors he considers important,. For example, if forage autonomy is a priority for a farmer, the prices associated with the lack of forages will be very high, and conversely if this is not a priority a low price will be set. The model does not perform an economic optimisation of the cropping plan, but aims at generating a cropping plan that is consistent with the farmer's goals, whatever the motives are. Likewise, the model FUMIGENE (Chardon *et al.* 2007) is used to generate yearly waste allocation plans, according to the fertilisation history and needs of each field, and to the management rules. In this case, the farmer's goals are modelled as a set of priorities associated with each field and with each combination of crop, waste and period. These priorities integrate the constraints and opportunities of the modelled farm. Both planning modules use information on the state of the system: the variation of stocks of feed, straw and wastes are included. For example, if in a given year the quantity of grass pasture is high and maize silage stocks are high at the end of the year, then the maize area can be decreased for the following year. The planning module is thus in interaction with the biotechnical system.

As mentioned above, the goal of the planning module is to generate an activity plan usable by the manager as defined in the ontology of agricultural systems. The cropping plan and the waste allocation must be translated into a proper activity plan. This is done through the use of general crop management plans. Each crop is associated with a fragment of activity plan, which includes all the technical operations required by the crop, including waste applications. This activity plan can depend on the preceding crop. When the cropping plan is generated, for each field, the relevant fragment of activity plan is duplicated and added to the manager's global activity plan. If no waste application was needed in the waste allocation, then these activities are removed from the plan.

In summary, MELODIE includes models of the decision-making processes of the farmers, which is relatively rare for models at this scale. The main strength of the decision system is the deep interactions with the biotechnical system, in the operational management during the year as well as in the planning step taken every year.

3. DISCUSSION

3.1. Ex-ante evaluation and system consistency

MELODIE was designed to perform ex-ante evaluations of farming systems. The goal is to evaluate different systems, existing or not, in the same context. The decision system relies on the paradigm of planned action. It is assumed that this paradigm leads to a realistic management, and the results, in terms of nutrient flows, are studied. A major difficulty is to ensure the consistency of the system simulated, particularly for those which do not exist in reality. For example, the cropping plan must match the feeding road map of the animals and the level of feed autonomy targeted by the farmer. In MELODIE, the planning module plays a key role in this regard, because it ensures the consistency of the different elements of the plan. To design a new system, it is necessary to provide the animal feeding road map, and the farmer's goals and priorities used by TOURNESOL and FUMIGENE. The cropping plan and the waste management plan are then automatically generated each year, so as to best match the goals defined by the model user. The consistency of the generated system depends on the consistency of the goals and their representation.

Another element of consistency in ex-ante evaluation is the capability of the decision-making process to cope with climate variability. In practise, management decisions can vary greatly between years, in terms of dates and parameters of the activities planned, and even in terms of activities executed. The plans must be flexible and leave room for context-dependent adaptation. In MELODIE, climate variability is taken into account at different levels, thanks to the interactions between the decision system and the biotechnical system. The dates and some parameters of the activities are determined by the state of the system, and on a yearly basis, the planning module integrates the variations of the stocks of feed and animal wastes. In the model, the management is thus automatically consistent with the state of the system, provided that the decision system is correctly modelled.

3.2. Model extent

In MELODIE, the environmental impact of production strategies is studied at the whole farm scale, because decisions are taken at this scale. Measures taken to reduce the environmental impact of farming have to be integrated into the production system, whose consistency must not be broken. Environmental impacts can be evaluated on many different criteria, which can be conflicting. Compromises between different environmental and/or economic objectives must be made, and this is only possible at the whole farm scale. An improvement on one criterion in one part of a farm is not necessarily a benefit at the farm scale. Indeed, the "best" production system is not necessarily the combination of the best practices at lower levels. For example, reducing ammonia losses during slurry storage increases the quantity of nitrogen to spread on crops, which might in turn increase the quantity of nitrogen leached. When comparing different management options, their indirect consequences should be studied.

As far as time is concerned, MELODIE operates on periods of several decades, and takes into account the climate variability between years. As mentioned above, climate does widely impact the nutrient losses of farming systems. It is necessary to study a production strategy on a sufficient number of climatic years for the results to be representative. One of the advantages of modeling is the ease of obtaining results for different climate series, once the model is built. The distribution of the values of the environmental indicators can then be studied, and probabilities of exceeding a given threshold can be calculated. Also, some environmental impacts of farming can only be noticed after such long periods. Some parameters of the system, like the nutrient content of soils, may vary with a long term trend. If the simulations are performed year by year, without carryover, the variability of climatic conditions can hide these slow changes. Therefore, in order to detect the cumulative effects (if any), it is necessary to perform long term simulations, rather than performing several independent one-year simulations. The structure of the farm and the management strategy do not change in the course of the simulation. The goal of MELODIE is not to make projections about what might happen in thirty years. The simulations are made on decades only in order to have a better understanding of the potential consequences of the farming strategies that are used or could be used today.

3.3. Rationale of the model granularity

Although the environmental impact should be evaluated at the farm scale, it is not easy to obtain data measured at this scale. Many studies in the literature focussed on describing the processes at a more detailed level. Modelling is a technique to upscale that knowledge to the farm scale. Therefore the choice was made to integrate models of processes at lower levels within MELODIE. This approach is complementary with the experimental studies. Furthermore, studies made at the farm scale, without considering the processes at lower levels, do not take into account the spatial heterogeneity of the environmental risks. For example, distributing the wastes evenly over the farm area or spreading them on only a few fields result in different nutrient losses. In MELODIE, in order to study this heterogeneity, nutrient flows occurring within the farm are simulated.

Likewise, the nutrient flows are dynamically simulated in order to evaluate the temporal variability of the risks. A given quantity of nitrogen leached can result in very low concentrations in the water during a long period, or in a peak during a few days. The consequences for the environment are different; therefore the dynamics of the nutrient losses within a year should be investigated. The daily time step for the simulation of these processes was chosen because it is used by most of the biotechnical sub-models. No sub-model had a time step lower than a day. This time step is used only for calculations. It is clear that for most processes, the sub-models are not accurate on a daily basis. The models were calibrated with data obtained on longer periods (weeks or months), and the dynamics at a daily time step are not known. However, the accuracy is better when the model outputs are considered over longer periods. The outputs of MELODIE at a daily time step should therefore be aggregated to a period of weeks or months.

3.4. Model applications

MELODIE is intended to be used in research and development, to compare the environmental impact of different production strategies in several series of yearly climatic scenarios. Setting up simulations is a long process, and the model produces large volumes of data to analyze. Therefore, MELODIE should be considered as a virtual experimentation framework, and the simulations should be designed like real experiments would be. MELODIE is not intended to be used on farm as a decision support system.

The main advantage of simulation, provided that validation has been done, is the ability to address time and space scales that are hardly manageable in real experiments. Furthermore, the model provides access to losses of the main nutrients considered in environmental impact studies, and from the different emission sources of the farm (animals, waste storage, fields). It is not possible to obtain such a large quantity of data from measurements. One resulting challenge is the treatment of large amounts of data: the outputs of the model have to be synthesized. A number of indicators of environmental impact have been proposed in the past. However, most of these indicators were designed to be easily calculated on farm, or from measured data. It is crucial for MELODIE to integrate indicators of environmental impact that make the most out of the model outputs. One possibility is to use indicators derived from Life Cycle Analysis (LCA). LCA provides references to calculate some synthetic indicators, starting from estimations of nutrient losses, which MELODIE can provide. These indicators are suitable evaluation criteria because they consider all the modeled nutrient losses and enable an evaluation of the whole system. However, they do not take into account the variability of the flows within and between years. Other indicators, based for example on frequencies, will be specifically designed for use in MELODIE.

3.5. Improvements for future versions

Projects of improvements of MELODIE include modelling labour and machinery resources. These factors are major constraints in most farms, and determine the execution of activities. However, several issues must be addressed. The labour availability in family-operated farms can hardly be modelled, because it is very variable in time and subject to constraints that lie far outside the farm. Many farms share some machines with neighbouring farms, and the availability of these machines depends on the needs of the other farms. Another issue is the competition between activities: when labour is a limiting factor, which activities should be performed? The priorities are likely to be very complex to determine and variable in time.

Finally, a central question when modelling decision making processes in agricultural systems, is the anticipation. If an activity can be delayed due to an unavailable resource, it can also be advanced. For example, some farmers might harvest grain earlier than the optimal date (accepting a decreased quality) because the harvester will not be available during the following days. Modelling anticipation involves the concepts of objectives, and the ability to predict the evolution of the system, which is a cognitive process of the farmer, independent of any model used in the biotechnical system.

4. CONCLUSION

As a conclusion, MELODIE is a framework for virtual experimentation on animal systems. Thanks to the association of a biotechnical model and a decision model, it enables a user to perform multi-criteria ex-ante evaluations of the impact of production strategies. Such evaluations are complementary with experimental approaches, and MELODIE can be extended to include new knowledge on nutrient flows and the underlying biophysical processes. MELODIE could also be extended to deal with other issues than nutrient flows.

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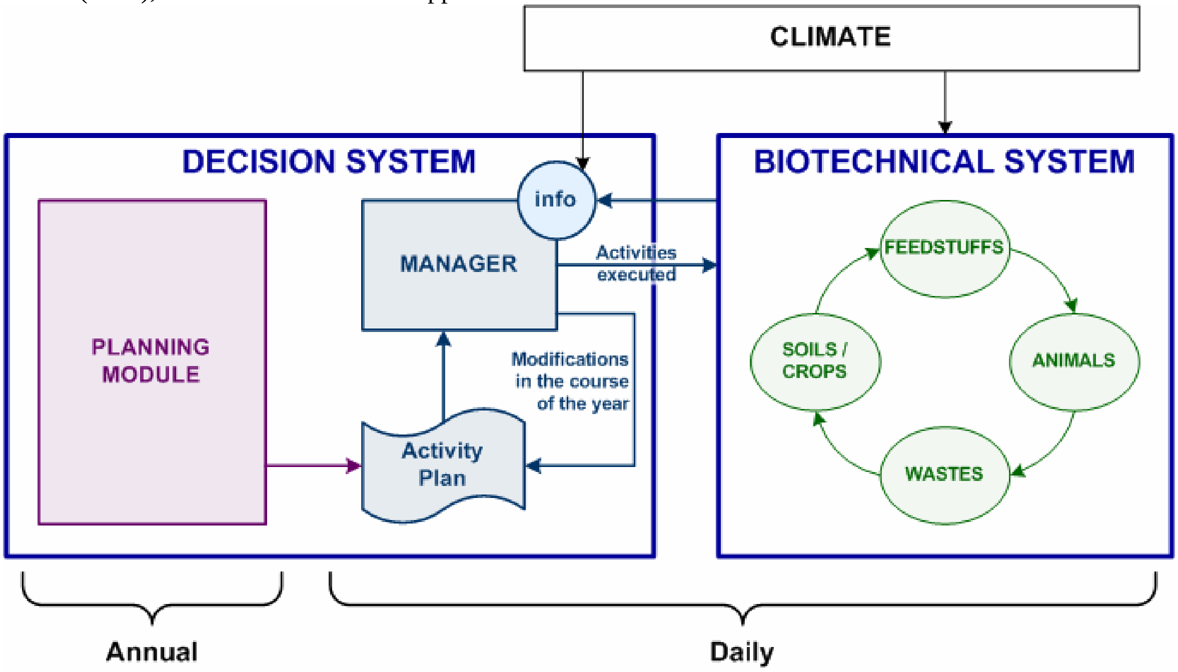

Fig 1 – General organisation of the different components of MELODIE. The decision system works with two time scales, and interacts with the biotechnical system, within which the nutrient flows are calculated daily.

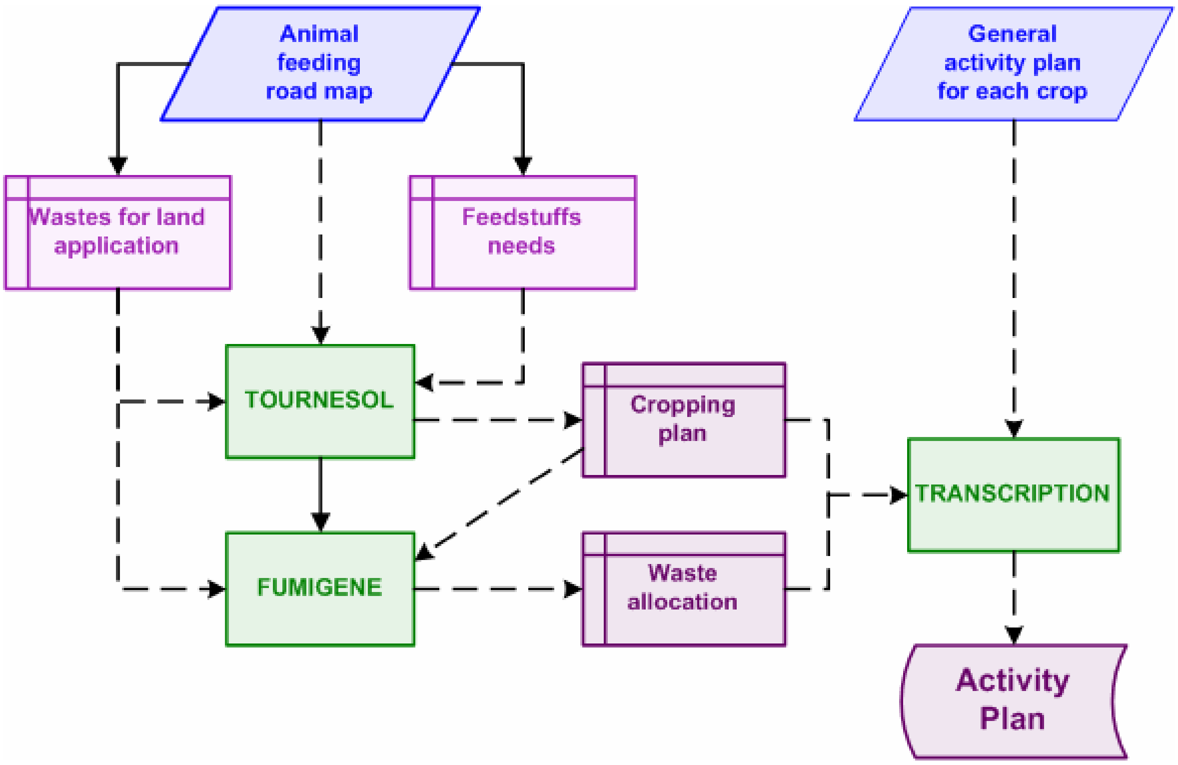

Fig 2 – Organisation of the planning module. The feeding road map is used every year to determine the cropping plan and the waste allocation, which are translated into a plan of activities to apply to the biotechnical system