Modelling Biomass Fluxes And Fertility Transfers: Animal Wastes Management In Reunion Island

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Abstract: The development of agriculture in Reunion Island encounters two problems related to the management of organic material. These are the risk of pollution generated by livestock farming (principally located in the highlands) and the loss of soil fertility (mainly in the lowlands, where sugar cane and vegetable crops are grown). A solution being considered is better organisation of the transfer of organic material from livestock units to crops, either for the individual farm or at the district level. To this end, we first study farmers' practices and then devise and test new management strategies. An interdisciplinary research program enabled us to build models to simulate these strategies with the aim of analysing current practices and aiding decision-making by agricultural stakeholders. Here we describe the problem and summarise our results. These are: (i) farm survey data generalised as conceptual models in the form of a farm classification and sets of management rules; (ii) several simulation models based on various modelling approaches (hybrid dynamical systems, agent-based simulation models); (iii) experimental data on some critical biophysical processes (mineralisation, ammonia volatilisation) in order to assess the environmental impact of waste management strategies. Using these models, either coupled together or in isolation, allows one to address a great diversity of management situations concerning: the operation of liquid or solid manure transfers at the farm level and risk assessment in terms of nitrogen released into the environment; the assessment of mass balance, technical parameters, investment/operating costs and supply policies of pig slurry treatment units using various processes; the transfers of organic material surpluses from livestock farms to recipient crop farms in rural areas; the assessment of environmental measures taking into account the economic behaviour of the farmers. The article ends with a critical discussion and an outline of future research plans.

Keywords: *Animal waste management; Farm classification; Conceptual modelling; Hybrid dynamical systems; Agent-based simulation; Reunion Island.*

1. INTRODUCTION

In Reunion Island[1], the development of livestock farms at the end of the 1980s resulted in large amounts of effluents in certain localities, with pollution risks largely due to the shortage of land on which to spread the material. Overall, these effluents represent more than 75% of the nitrogen in the waste organic products of the island. Moreover, as often in the tropics, the crops need a large application of organic matter to maintain the fertility of soils which are subject to serious erosion. The imbalance between small areas of the island is getting worse: some of them produce carbonaceous biomass (such as sugar cane in the lowlands), while others in the uplands produce nitrogen-rich effluents, largely from imported feedstuffs. Currently therefore there is an imbalance in the agricultural practices: on the one hand we have poorly used waste material which is a pollutant, and on the other an unsatisfied demand for organic manure. Meanwhile the French and European regulations, which reflect society's expectations as regards the quality of the environment, are becoming more and more restrictive. The sustainability of livestock systems is therefore conditioned by their capacity to dispose of their own waste products whilst respecting environmental, agronomic, technical, economic, social and regulatory constraints.

This challenge is found in other regions with specialised intensive agriculture, such as Brittany in western France, but it is worse in Reunion because of it being an island. The export of low-value polluting material is out of the question and yet the pressure exerted on the land by various factors such as agriculture, building, tourism, and nature conservation leads to the intensification of

1 Reunion is in the Mascarene Islands with Mauritius and Rodrigues, in the Indian Ocean, east of Madagascar.

livestock systems, the concentration of produced effluent, and thus it becomes impossible to spread this effluent within the conditions required by the regulations because of land shortage.

The required control of livestock effluent involves finding methods of sustainable management so as to match up, in terms of both quantity and quality, the supply of livestock effluent with the demand for organic matter by crops, for a particular region. To study these fertility transfers we have considered two management levels for organic matter (OM): (1) the farm (individual level), where the transfer from the livestock to the crops has to be organised; (2) the region (collective level), where the transfers have to be arranged from those farms with a surplus (predominantly with intensive livestock) to those with a deficit (predominantly producing crops). At these two levels, the qualitative adaptation of the effluents to the needs of the crops may involve their transformation (for example into compost). The creation of treatment plants, either on the farm or under collective management, has therefore been considered as part of this process.

Our approach has been to construct simulation models from an analysis of the practices of the agricultural stakeholders and from agronomic data, some of which had to be obtained by experimentation. In return, the management models created should enable strategies to be compared in terms of their agronomic efficiency, environmental risk, cost and technical feasibility, so as to offer them to farmers, advisors etc. (Fig. 1).

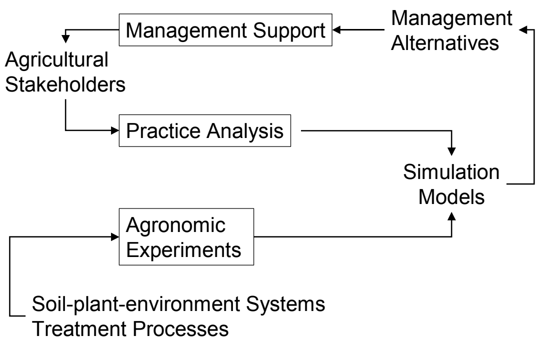

Figure 1. Model-based decision support for animal waste management.

Three objectives were agreed:

1. The construction of models to simulate the management of organic matter fluxes at the individual and collective levels and their interaction using the device of a "system of models".

2. The evaluation of current management strategies and the formulation of new strategies at these two levels.

3. The evaluation of agronomic and environmental impacts by coupling management models with models of the biophysical processes involved.

We summarise in section 2 our main results and give, section 3, a critical discussion about the validation and the use of models as management aids, and an outline of our future research plans. A full presentation of this work performed within a 4-year interdisciplinary research program may be found in Guerrin and Paillat, 2003.

2. WORK CARRIED OUT

2.1. Practice analysis

The study of practices for animal waste and soil fertility management has involved numerous farm surveys carried out from 1995 until 1999 in different parts of the island so as to take account of the differing types of situation (Fig. 2).

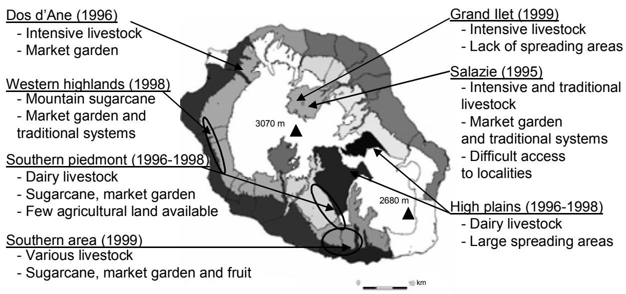

Figure 2. Map of the main cropping areas of Reunion showing the siting and year of field studies.

For example at Grand-Ilet, the available area for manure spreading is not enough to cope with the large production of manure from intensive pig and poultry units. In the south, on the other hand, the various types of crop production (sugar cane, forage crops, market gardening, fruit crops) and animal production (pigs, poultry, dairy cattle) and the proximity of the sugar cane area mean that these problems are less acute. Altogether there are 192 farms whose characteristics, both structural and as regards OM management, were entered into a database. By using the ratio between livestock units and the area of agricultural land as the main criterion, the farms were classified, revealing three main types (I: predominantly intensive livestock; II: mixed crops and intensive livestock; III: predominantly crops) which are divisible into 9 sub-types (Fig. 3). By combining all these subtypes with the main agro-ecological regions found in Reunion (littoral zone, foothills, cirques, plateaux) and the type of animal production (cattle, intensive livestock) one obtains 26 types of farm representing the full range of OM management problems to be found in the island.

From more specific surveys (Fig. 2: southern area and Grand-Ilet in 1999), an "action model" (Papy, 1994) bringing together most of the structural data and the farmers' management rules has been formulated (Aubry, Paillat, and Guerrin, 2001). This conceptual representation is made up of modules corresponding to the organisation of effluent management within farms (Fig. 4).

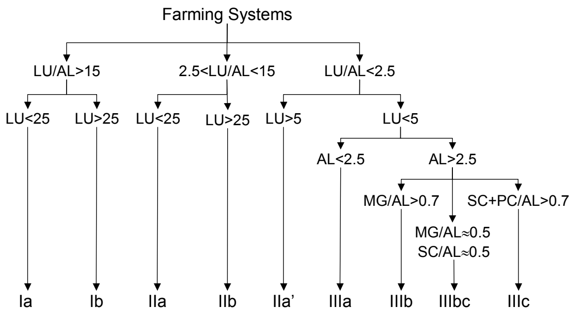

Figure 3. Farm classification based on livestock waste management in Reunion Island (LU: livestock unit; AL: agricultural land; MG: market garden; SC: sugar cane; PC: perennial crops).

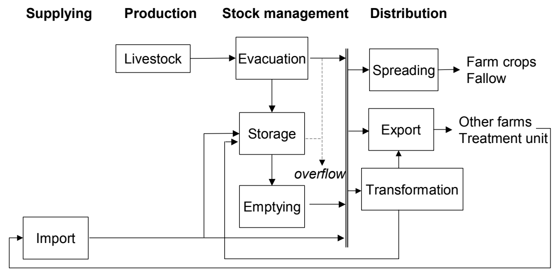

Figure 4. Representation of effluent flows in a farming system.

This study reveals certain striking aspects of the place of organic matter in Reunion's agricultural practices. Among these, the farmers' lack of awareness of the manurial value of the animal waste is worrying for the sustainability of agriculture because of the pollution risk and nuisance caused by spreading huge amounts, in breach of regulatory standards and good practice, just where savings could be made in the inputs.

2.2. Management models

Several mathematical or computer models have been constructed from information formalised in the action model (cf. §2.1). They allow a great many examples of livestock effluent flux management to be simulated:

1. within a farm: the *Magma* model (Guerrin, 2001);
2. between distinct farms: the *Biomas* (Courdier *et al.*, 2002) and *Mens* models, the latter giving, in conjunction with Magma, the *MagmaS* system (Martin *et al.*, 2001);
3. for the supply of collective treatment units: the *Approzut I* (Guerrin and Ranaivosolo, 2001) and *Approzut II* (Hélias *et al.*, 2001) models;
4. to select and determine the size of a treatment plant for pig slurry: the *Macsizut* spreadsheet which can be used to calculate, for different processes, the matter balances and to estimate the investment and running costs;
5. to evaluate the effects of environmental policies on the economic behaviour of the stakeholders: the *Echos* model (Farolfi *et al.*, 2002), taking account of the management costs at the individual and collective levels, and the legislation concerning animal wastes.

Because of lack of space we cannot present here many examples of how such models may help assess management strategies. For this, one should report to the cited publications. However, Fig. 5 shows a typical output of Magma.

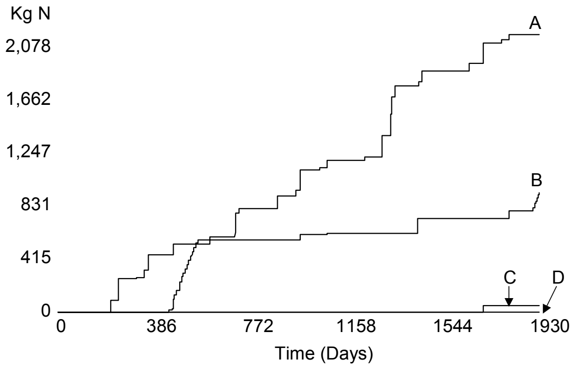

Figure 5. Accumulated amount of N 'illegally' released into the environment (i.e. stock overflows, over fertilization of crops, and spreading on fallows) according to 4 strategies simulated with Magma on 5 years for a type IIb farm in Reunion (A: spreading raw OM on crops; B: same with composting; C: same + 1ha of forage crop; D: mixing B and C strategies).

As to methodology, we are interested in hybrid dynamic systems with which one can represent complex systems by both continuous and discrete variables (Antsaklis, Koutsoukos, and Zaytoon, 1998). This approach was used to develop the Magma and Approzut I and II models.

To tackle collective waste management, two approaches based on multi-agent systems have been used: one in which each farm is represented by a group of interacting software agents (Biomas and Echos); another (MagmaS), where the farms are represented by instances of the Magma model connected to the multi-agent platform Cormas (Bousquet *et al.*, 1998). In both approaches OM transfers are based on transactions among farmer agents.

Certain of these models, together with a model of biophysical processes (see §2.3), have been coupled, thus providing a rough outline of the "model system" which was one of our objectives (Fig. 6).

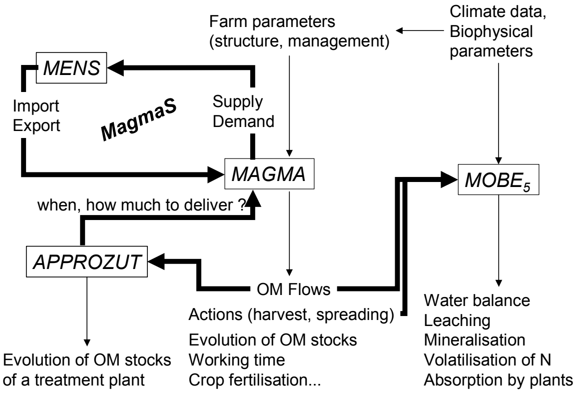

Figure 6. Coupling of simulation models to assist animal waste management (model connections appear as thick arrows).

2.3. Agronomic and environmental assessment of OM management strategies

Overall, in Reunion, the sources of nitrogen were estimated to average 9,100 tons of N/year (3,100 tons as locally produced organic wastes and 6,000 tons as imported chemical fertilizers). An exercise to classify and map the cropping systems of Reunion has, by mapping the yields of the main crops (sugar cane and pasture), provided also an estimate of the potential for utilisation of the OM and located these pits of nitrogen. The potential crop needs are 7,855 tons of N/year (of which 665 tons for market gardening and fruit crops, 3,000 tons for sugar cane, and 4,190 tons for forage crops). The apparent balance let thus appear "environmental leaks" of 1,245 tons of N/year as volatilisation, soil immobilisation, runoff and leaching flows.

To test animal waste management strategies it is necessary to be able to describe and quantify their agronomic efficiency and their environmental impact. Four main processes were thus considered by taking nitrogen as the principal element: gaseous emission into the atmosphere (mainly as ammonia), mineralization and immobilisation in the soil, runoff and leaching into aquifers, and absorption by plants.

In view of the absence of data from Reunion on the first two of the above cited processes, experiments were carried out to study: (i) ammonia volatilisation in two typical situations found in Reunion: cattle slurry spreading on upland grassland on andosols and pig slurry spreading on sugar cane, with or without mulch, on a brown ferralitic soil; (ii) nitrogen and carbon mineralization in eight soil types and nine types of effluent spread onto the two main Reunion soil groups (andosol and brown ferralitic).

The use of biophysical models was considered to assess the impact of spreading fluxes simulated with Magma according to various management strategies. A set of already published mechanistic models (like *Stics*, Brisson *et al.*, 1998; and *Stal*, Morvan, 1999) was integrated within the same simulation framework. This resulted in *Mobe5*, a system which simulates volatilisation, leaching, mineralization, and absorption of nitrogen by coupling with Magma (Fig. 6).

However, the data available on the dynamics of nitrogen absorption by plants and leaching of soils in Reunion finally turned out to be insufficient to parameterise either Mobe5 or Stics. Although simulations are technically feasible using sets of parameters measured in European conditions, they cannot yet be used to reliably estimate the effect of spreading in the context of Reunion.

However, the knowledge gained through the experiments that were performed makes it possible, now, to formalize some empirical rules that could be used to assess (even roughly) the potential agronomic efficiency and environmental risk of simulated management strategies. For example, some of these rules are:

- *In the dry and windy season (June to November) one can expect the volatilisation rate of ammonia nitrogen of slurry spread on sugar cane to be 100% with mulch and 50% with bare soil;*
- *In wintertime, one loses 40% of the ammonia nitrogen of slurry spread on grassland;*
- *The proportion of ammonia and organic N is 65%-35% for pig slurry, 40%-60% for cattle slurry.*

Similarly, some empirical functions can be derived from data: kinetics of mineralisation for various organic materials, relationship between leaching and rainfall, etc. The absorption rate of nitrogen by a given crop could even be estimated as the ratio between its annual needs of N and the length of the growing period.

3. DISCUSSION AND FUTURE PLANS

3.1. Comparing our results with our aims

Having completed several models representing the three main management situations identified (OM transfers within and between farms and the supply of a collective treatment plant), our first objective is largely complete. As regards modelling methodology, our main contribution is concerned with the integration of different modelling formalisms (multi-agent systems vs. dynamical systems, continuous vs. discrete variables) and the coupling of models (Fig. 6). Another contribution is the formalisation of conceptual representations (classifications, action models) to be used for analysing effluent management systems and as a basis to implement computer models.

However, our second objective, the evaluation of current and new management strategies, has only been partially attained, since our models have not yet been fully exploited. However, this exploitation will be done in the follow-up to this early work by performing the thorough analysis of the farming systems represented. This analysis can eventually enable all possible information about management to be extracted and confronted with real farms issues.

The evaluation of agronomic and environmental impacts by coupling together management and biophysical models, that was our third objective, has clearly failed. The reason is the lack of local data to parameterise models like Mobe5 or Stics for some processes (absorption of N by plants and leaching). The work on nitrogen and carbon transformations and ammonia volatilisation underlines, however, the value of acquiring data on these processes in the tropical environment. This acquisition will no doubt require considerable experimental effort. In the meanwhile, the extraction of rules and empirical functions from available data is foreseen (see §2.3).

3.2. Questions raised about models

The object of a "management aid" from the point of view of our work raises three major questions: (i) model validation; (ii) model use; (iii) system management and biophysical knowledge integration.

The first question concerns the validation of models, which is strongly related to the objectives they are assigned to. With a predictive viewpoint, model simulations are intended to represent as closely as possible the changing reality of a range of farms. However, apart from the subjective comparison of simulation outputs with statements by expert agronomists or farmers, it seems illusory to objectively validate such models against complex systems in which measurement is difficult. Now, if we consider models as a tool to better understand how farming systems work the validation criterion is different. The aim is no longer to precisely predict the future but rather gaining general, even imprecise, knowledge by experimenting alternative management strategies and exploring their possible impacts. This is why, after having already performed the first step of expert validation, we foresee, now, the use of our models in partnership with agricultural stakeholders (farmers, advisors) so as to validate them as decision aids in solving concrete problems such as that of the surplus of animal wastes in Grand-Ilet.

The second question stems from the choice of the target group of decision-makers envisaged. Our approach was directed primarily at "individual" decision-makers, namely the farmers. The idea was that if one wishes to modify practices, one must work with the situation which applies to the person concerned. This means playing with the model in company with the farmer until a solution is obtained. This solution must be sufficiently convincing that one might hope it will be then put into practice. For this purpose, the credibility of the model is a prerequisite which requires that it should represent as accurately as possible the specific conditions on each farm. Knowing the variations of management rules, not only from one farm to another, but within a single farm, one may wonder whether this objective is really attainable unless the model itself becomes the reality! The question therefore arises as to how far to go, in the quest for realism, in the sophistication of models, which become increasingly complex, increasing the amount of information needed for the simulations and the difficulties in interpretation. It now seems more realistic to us to regard the model as a conceptual support for technical users (agronomists, advisors) who have to develop new management strategies which are then to be offered, debated, and negotiated with the farmers without using the computer. Further, the experience gained with models in operational situations may be transmitted, together with other sources of expertise, at the level of political decision-makers in search of better practices or innovative solutions.

The third question is to do with the execution of experimental studies on the biophysical processes in relation to a study of management. These experimental studies are difficult, lengthy, expensive, and they will not just be a matter of providing models with data because they possess an intrinsic scientific value. They are made "at best" at the scale of a plot, and "at worst" of a column of soil, an incubation chamber or an effluent treatment plant. Inasmuch as the management objectives are concerned with the general level of production systems and in trying to operate at the scale of a locality or indeed the whole island, there could be a confusion of levels and scales which is prejudicial to the objectives aimed for.

The precision of the data may be excessive at the levels and scales which we are interested in, for there is a real risk of a drift towards "analysis" to the detriment of an approach which ought to be "holistic". A better homogeneity is the benefit that we expect from general rules and empirical functions, stemming from the studies on soil-plant-atmosphere systems, to be integrated within management models to assess the agronomic efficiency and the environmental impact of simulated strategies.

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