MANAGEMENT OF LIVESTOCK EFFLUENTS IN RÉUNION
Use of a multi-agent system to analyse the economic behaviour of players

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ABSTRACT

This study uses a multi-agent model to illustrate the behaviour of economic players in a context of rapidly evolving environmental policy. The area under study is represented by a sector of Réunion island with a high concentration of pig farms (Grand Ilet) in the upland region and extensive sugarcane plantations in the coastal zone. The pollution problems associated with pig rearing are being addressed by the public authorities, which must choose a set of environmental measures suited to the local context. After illustrating the approach and the results that can be obtained using multi-agent systems model reality, we discuss their advantages for the implementation of decision-making and negotiation tools.

1 INTRODUCTION

The effluents resulting from livestock production (manure, slurry) are rich in nitrogen and phosphorus. Though they are good fertilizers, they represent a source of pollution when present in massive amounts. In zones of high-density livestock production, the persistent accumulation of elements such as nitrogen is a frequent problem. These zones are referred to as structural excess zones.

In order to protect the environment, rules have been establish to regulate the spreading of these effluents on farmland (Ministerial orders of 1992, modified in 1999, Code of Good Farming Practice, 1994, Nitrates Directive, 1991). Under French law, livestock farms are "environmentally sensitive installations" (laws on environmentally sensitive installations (ICPE) of 1976 and subsequent modifications) and the new water law provides for a pollution charge to be levied on livestock producers.

In a context of rapidly evolving and increasingly stringent legal requirements, stock breeders are faced with a new system of constraints and, perhaps in the near future, economic instruments (taxes, subsidies) which will modify their approach to effluent management.

Though the tropical climate of Réunion and hence the cycle of nitrogen use by crops (higher plant productivity, different mineralisation kinetics) is very different from that of the French mainland, the island is nevertheless subject to French regulations.

Our study concerns the economic behaviour of livestock breeders in Grand Ilet, an area of Réunion Island with a high concentration of livestock farms, pig breeders in particular. These breeders face the problem of how to deal with large quantities of excess slurry, which they cannot dispose of by spreading as they do not have sufficient arable land. Moreover, they grow mainly vegetable crops, on which slurry spreading is prohibited. Indeed, if the rules were followed to the letter, it would be practically impossible to spread the slurry produced in Grand Ilet.

Our model is based on data and information collected and analysed by the GDOR team of CIRAD TERA, notably that contained in the work of F. Guerrin and J.M. Paillat (1994-2001). It forms part of the "environmental economics" research theme of the CIRAD thematic action programme 99/60 entitled "Biomass flow and fertility transfer modelling. Management of livestock effluent in Réunion."

2 ECONOMIC ANALYSIS OF PLAYERS' BEHAVIOUR

We chose to use multi-agent systems (MAS) to interpret the economic behaviour of Grand Ilet pig breeders on the basis of different scenarios of environmental policy enforcement. The use of MAS enables us to combine several different components for the representation

of reality. In particular, we were seeking to combine both economic and ecological dynamics in a spatialized model. The agents studied may have different strategies and may sometimes evolve during a simulation. In other words, multi-agent modelling enables us to illustrate certain mechanisms that are difficult to pinpoint using standard economic modelling methods.
The agents of our model are assumed to be rational and well-informed. However, economic players who are not entirely rational or only partly informed can also be included in a MAS. These types of behaviour, not described in this paper, will be included in future project developments.

2.1 Multi-agent approach

Multi-agent systems comprise sets of interacting computer entities with varying degrees of autonomy. They have grown in importance over recent years and have led to the development of a new branch of research known as distributed artificial intelligence (Ferber, 1995)[7]. Research in this field follows two distinct paths: modelling and simulation of natural mechanisms and the distributed resolution of complex tasks. The use of MAS is now widespread among researchers in the social sciences. The system comprises four components: an environment, agents which can interpret this environment, interaction systems and an organization (Dupuy, 1994) [5]. Simulations are performed to test hypotheses concerning real organizations and interactions and to identify the minimum set of processes required for certain characteristics of a group to emerge (Rouchier, 2000) [15].
Recent studies (Bousquet et al. (1999)[4], Antona and Farolfi (2001)[1], Rouchier et al. (2000)[16]) examine the use of MAS to build economic models representing the use of natural resources by a set of agents or to study possible processes of change.
Guerrin et al. (1998)[8] have developed a multi-agents model (Biomas) representing livestock effluent management practices in Réunion. This model, which gives a detailed illustration of farming practices, does not take account of organic matter management costs, with the exception of transport costs. This means that the consequences of environmental regulations on the economic behaviour of breeders cannot be studied with this tool.
Multi-agent systems enable researchers to focus on certain factors that are difficult to assess using the mathematical modelling tools widely used by neoclassical economists. More precisely, MAS allow economists to consider at the same time the following concerns:

- by incorporating the spatial dimension into the logic of the model, MAS can be used to study livestock effluent disposal by spreading;
- multi-agent simulations give a clearer picture of environmental dynamics (nitrogen concentration in the soil) and economic dynamics (cost of effluent management), enabling us to study our problem from both economic and ecological viewpoints;
- MAS are also able to represent different types of player and, within a single group of players (e.g., livestock breeders) to represent agents that differ in terms of farm size, management strategy, geographical location, etc.;
- lastly, problems of environmental impact such as accumulation of excess organic matter in the soil, must be analysed over a long period. The time component is therefore very important and MAS, which are simulation tools, incorporate this dimension within the very dynamics of the processes under study.

2.1.1 Model structure and operation

Our research focused on the use of MAS to simulate the implementation and impact of environmental policy instruments in the pig breeding sector on Réunion Island.
The rational and well-informed pig breeder in Grand Ilet minimizes his pollution control costs while being fully aware of developments in environmental legislation, available technologies and the strategies of other economic and institutional players. We wanted to include sugarcane growers, since we believed that sugarcane plantations might be an attractive solution for the disposal of pig slurry produced in Réunion. (1).
The public institution, for its part, defines the legal and economic instruments of environmental policy required to reach economic, social and ecological objectives. Here, we will focus on the combination of economic instruments (pollution charges) and legal instruments (maximum authorized organic nitrogen input per hectare)(2).

(1) In response to the exorbitant quantities of nitrogen provided to crops by slurry spreading in Grand Ilet (more than 1.5 t/he per year on each cultivated plot) (Renault-Paillat, 1999)[13] and the environmental problems associated with this practice, a number of solutions have been proposed. One involves exporting the liquid effluents outside the Grand Ilet zone, to crops such as sugarcane which require large quantities of organic matter. Another solution would be to transform the liquid effluents into more manageable solid products for use on the crops of pig breeders', other farmers and vegetable growers outside the zone. This second option, which could be achieved by installing a collective composting station for example, is not taken into account in this paper.

(2) Under the "Nitrates" Directive of 12 December 1991, France has launched a long negotiation process which led to an agreement (the agricultural pollution control plan - PMPOA) between the French government and farmers' organizations on 8 October 1993. The system finally adopted can be described quite simply: in order to reduce pollution, livestock breeders must perform the works required to bring their facilities into compliance with regulations covering environmentally sensitive installations (law no. 76-663 of 19 July 1976 and subsequent modifications) and must undertake to modify their farming practices. The central point of this programme is the definition of maximum spreading limits according to the vulnerability and degree of pollution of land on which spreading may be performed. In structural excess zones, the authorized maximum is 170 kg of nitrogen per hectare. This limit is raised to 200 kg of organic nitrogen /ha on crops and 350 kg/ha on meadows outside structural excess zones. The state,

Model structure

In this model, called Echos, three groups of players are represented: the Grand Ilet pig breeders, the sugarcane growers in the coastal zone and the public authority which defines environmental policy.

From a spatial viewpoint, the model covers an area of around 100 km^2 (10,000 ha) between Grand Ilet and the coastal zone. Fifty-six pig farms are represented and six sugarcane plantations.

The area is divided up into a regular grid. Each spatial unit or cell on the reference grid corresponds to one hectare, giving an accurate graphical representation of each farm (see figure 1).

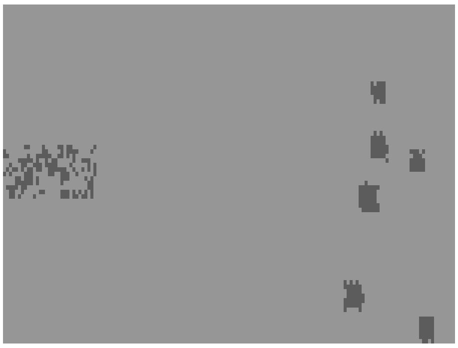

Figure 1: *Simulation area in the Echos model. Small Grand Ilet farms (on the left) and large sugarcane plantations (on the right).*

The grid is divided into three zones: Grand Ilet, a non-cultivated zone between Grand Ilet and the coast, and a coastal zone where sugarcane is grown.

The pig farms are represented in a simplified manner as a random combination of fallows (50% of surface area) and crops (50%). For the "crop" zones, we allocated a nitrogen absorption capacity of 387.6 kg/year (weighted average of the absorption capacity of crops present, Renault-Paillat, 1999 [13]), while for the fallow zones, the absorption capacity is zero. The real absorption for fallows in Réunion is close to zero. We chose to put 0 in the model in order to clearly separate "crop" and "fallow" absorption capacity. To this value we added an organic nitrogen loss rate, which is independent of the crops grown, and which is the same for all types of land (3.6% per year). Diffusion is calculated as a fixed quota of the total nitrogen in the cell.

For the parameters corresponding to sugarcane nitrogen requirements and for pig breeder nitrogen production figures, see notes (3) and (11).

Fifty-six pig farms were included in the model. According to Renault and Paillat (1999) [13], they are divided into three types, depending on the sows and litters/land in use ratio (intensity level): Type 1: sows and litters/land in use >10 (36); Type 2: sows and litters/land in use 3<x<10 (15); Type 3: sows and litters/land in use <3 (5).

Pig farms' size range is between 1 and 50 sows and litters as well as between 0,5 and 8 ha.

Constant pig production during the simulation time is assumed.

Six sugarcane plantations are located in the coastal zone. Their surface area, between 20 and 40 ha, is attributed randomly by the model for each simulation.

Dynamics

The time unit is the month. The areas suitable for effluent spreading in Grand Ilet can be modified in the model. In the simulations which follow, each breeder has just one choice: he is able to spread his effluent either on his own fields or on those of neighbouring farmers (if the land is available and if the farmer is authorized) within a radius of 1 km.

A method was defined to simulate the spread of nitrogen pollution across sloping land. Each month, 10% of the nitrogen present in a cell spreads to downstream cells, with 50% of this amount going to the eastern cell and 25% to the north-eastern and south-eastern cells.

The sugarcane growers act as follows. Once a year, they spread on their fields a quantity of nitrogen corresponding to annual sugarcane demand(3). If there is no effluent trade with the breeders, they buy mineral fertilizer. If the nitrogen they spread comes from effluent supplied free of charge by the pig breeders, they may also buy mineral fertilizer to provide additional nitrogen input. For the calculation of the costs of each strategy, see the appendix.

We used the observations and data contained in [2] and [13] to simulate the effluent spreading practices of the Grand Ilet pig breeders. In particular, an effluent storage capacity was allocated to each producer. This capacity is reached every four months on average, upon which the breeder empties his tanks.

We defined a number of spreading strategies:

- Strategy 0: the pig breeder spreads all his effluent onto his own farm, in a regular manner;
- Strategy 1: the breeder starts by spreading effluent on his own farm, in compliance with environmental legislation. He then approaches neighbouring

the local authorities and the water agencies agree to contribute to the investments required to perform the necessary works. In return, breeders entitled to financial aids are subject to the pollution charge levied by the water agencies. In particular, the new water law, due to come into force in 2001, contains for the first time a specific charge for excess nitrogen. For the first time, diffuse pollution of agricultural origin is subject to taxation. According to certain observers (Nadeau, 2001) [9], it will be calculated by establishing an input/output balance. The charge will be 2 to 3 francs per unit of excess nitrogen.

(3) Pig slurry in Réunion is more dilute and less nitrogen-rich. One tonne of pig slurry in Réunion contains, on average, 4 kg of nitrogen (Renault-Paillat, 1999) [13], while the mainland reference is 5 kg/N tonne. The annual nitrogen requirement for sugarcane in Réunion is estimated at 200 kg/ha by certain authors (Reynaud, 1995) [14], and 100 - 150 kg/ha by others (Baldoni-Giardini) [3]. The union of farming cooperatives in Réunion affirms that the common practice is to spread 1 tonne of 15.12.24. fertilizer per hectare of sugarcane, corresponding to 150 kgN/ha.

breeders (within a 1 km radius) to find out if any land is available for spreading his effluent in compliance with legal limits. Lastly, if after spreading on all available land to within legal limits he still has not disposed of all his effluent (pollution subject to charges under the law), he spreads the remainder on his own land;

- Strategy 2: identical to strategy 1, except in the case where he still has effluent to dispose of after spreading on all available land to within legal limits. In this case, he takes the remaining effluent to the coastal sugarcane growers, with preference for those located closest to his farm. If no sugarcane growers want his effluent, he spreads it on his own land;

- Strategy 3: we introduce the pollution charge. Moreover, the effluent management costs for breeders and the cost of sugarcane fertilization for coastal growers are also taken into account. At the end of each year, on the basis of cost forecasts for the two previous strategies (1 and 2), the breeder decides to adopt strategy 1 or 2 the next year. Note that at this modelling stage, the strategies 1 and 2 correspond to rules a) and b) of the mathematical model in the appendix.

For transport to the coastal zone, we assume that the only means available to breeders is a tractor and trailer with a capacity of 10 m^3. No breeder will take his effluent to the sugarcane plantation if his effluent stock is below this threshold.
Figure 2 illustrates the flow diagram of a time step corresponding to the breeders' strategy 3 in the Echos model.[(4)].

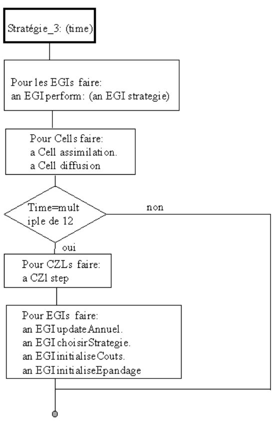

Figure 2: *General control flow diagram in the Echos model: 1 time step.*

[(4)] In the computer program, EGI = Grand Ilet breeders and CZL = Coastal sugarcane growers.

2.1.2 Simulation results

The purpose of the model is to simulate dynamics both in terms of pollution (nitrogen concentration in the soil) and in terms of costs for breeders of complying with environmental requirements, and the effluent management choices made as a consequence.
The available effluent management alternatives for strategy 3 are: **a)** spreading of all organic matter (OM) on the farm or on neighbouring Grand Ilet farms (strategy 1); and **b)** effluent transport to sugarcane plantations along the coast (strategy 2).
The different alternatives are analysed by the model using simulations which determine the total pollution at Grand Ilet and in the coastal zone and the costs borne by breeders and by the community for the management of this pollution.
We present below four simulations over a ten-year period, with modification of the following parameters: legal spreading limits, pollution charge and surface area of sugarcane plantations.

Scenario 1: Spreading limit: 170 kgN/ha; pollution charge = 0; sugarcane plantation size: 20ha$<$x$<$40 ha.
The application of the spreading limit defined for structural excess zones in the Nitrates Directive is not associated with a financial sanction, nor with a charge applicable to excess pollution. So there are no economic incentives to incite the Grand Ilet breeders to change their customary practice of spreading all their effluent on their own fields or those of their neighbours (within a 1 km radius). The absence of economic instruments to enforce environmental policy results in a status quo. This means high pollution levels concentrated in Grand Ilet (fig. 3). The curve of nitrogen in the environment (fig. 4) after ten years is still increasing and is well above 200 tonnes. There is no transport of effluent from Grand Ilet to the coastal zone so the sugarcane growers buy mineral fertilizers throughout the simulated period (fig. 5) and the cost of OM management for breeders remains unchanged. (fig. 6).

Scenario 2: Spreading limit: 170 kgN/ha; progressive pollution charge (2 F/kg excess nitrogen every 2 years); sugarcane plantation size: 20ha$<$x$<$40 ha.
In this scenario, we test the efficacy of pollution charges as an incentive for breeders to change their strategy. The charge is applied to breeders who spread quantities of effluent at Grand Ilet in excess of the legal limit. The charge is calculated in francs/kgN and is progressive over the simulated period. There is no charge during the first two years. From the third year it corresponds to 2 Frs/kgN and every two years it increases by a further 2 F/kgN. In this simulation, the agents perceive the effects of the charge only at the end of the year. In other words, they are not sufficiently informed about changes in environmental policy and their behaviour is based not on forecasts but on an analysis of their costs

over the previous season, which they compare with a possible alternative strategy (for which they do not have all the necessary information either [5]). During the first three years, only three breeders decide to change their strategy, though the next year they revert back to the previous solution[6]. From the fourth year, practically all breeders (49 out of 56) decide to transport their effluent to the coastal zone, where demand for slurry is rapidly saturated (fig. 5). From the fifth year, nitrogen demand from sugarcane growers is fully satisfied by effluent from Grand Ilet. The subsequent increase in the pollution charge proves unnecessary (2 F/kgN is already effective) and simply increases unnecessarily the social cost of the policy by forcing breeders to pay extra charges (fig. 6). In terms of pollution control, figure 3 clearly illustrates the positive effect of economic incentives and is confirmed by the graph in figure 4. However, once again, an increase in the pollution charge above 2 F/kgN appears to be unproductive, since environmental pollution stabilizes from the fourth year. Further economic measures, all other things being equal, are therefore unproductive.

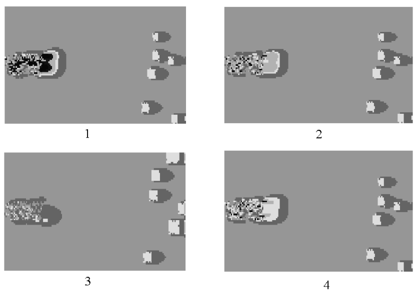

Figure 3: *Pollution in the zone at t=10 years, for the four scenarios.*

Scenario 3: Spreading limit: 170 kgN/ha; progressive pollution charge (2 F/kgN every 2 years); sugarcane plantation size: 40ha<x<80 ha.

This scenario shows the importance of the territorial factor in the choice of environmental policy. The same measures are adopted as in scenario 2, though the size of plantations in the coastal zone is doubled.

This scenario shows the importance of the territorial factor in the choice of environmental policy. The same measures are adopted as in scenario 2, though the size of plantations in the coastal zone is doubled. (fig. 5), though this time the absorption capacity of the coastal zone is larger and practically all Grand Ilet breeders are able to find takers for their effluent. This results in the transport of much larger quantities of nitrogen and very low environmental pollution after ten years (fig. 3). In this case, the application of a pollution charge greater than 2 F/kgN, though still unproductive, is justified with regard to the previous scenario as it offers a strong incentive to adopt a strategy that reduces environmental impact. Moreover, provided that the breeders change their strategy, the consequences of a progressive charge in terms of pollution management cost would be less hard-hitting than in the situation illustrated in scenario 2 (fig. 6). With the application of economic measures, the nitrogen in the environment, which increased faster than in all previous scenarios when the charge was zero due to fertilization over a larger area of sugarcane production (fig. 4), initially decreases and stabilizes at a level below all other cases. This is without doubt the most optimistic scenario, with all indicators pointing to positive results.

Scenario 4: Spreading limit: 300 kgN/ha; progressive pollution charge (2 F/kg every 2 years); sugarcane plantation size: 20ha<x<40 ha.

In this final scenario, with conditions similar to scenario 2, we wanted to tests the effects of changing the effluent spreading limit. Given that the coastal area is not large enough to absorb all excess slurry, an increase in the spreading limit to 300 kgN/ha would, after ten years, result in pollution levels similar to scenario 2 (fig. 3 and fig. 4) but with a lesser social cost (fig. 6). The decision to change the spreading limit would, in this case, be based on knowledge of how much land is available for

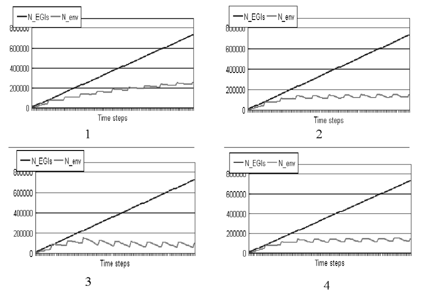

Figure 4: *Pollution produced by breeders versus environmental pollution at t=10 years, for the four scenarios.*

[5] For example, to change from strategy **a** to strategy **b**, the transport cost is estimated over a hypothetical distance and not over the real distance from sugarcane growers, a factor which remains unknown until the end of the season; This means that the forecast cost does not correspond exactly to the real cost.

[6] In fact, the decision to change to strategy b), even if the pollution charge is 0, depends on the way in which the predicted cost for the following year is calculated. Quantities of effluent below 40 kgN are not transported since the breeder only makes the journey with a full trailer. So if, for example, the annual quantity of nitrogen to be spread for a pig farm is 245 kg over an area of one ha, 170 kg will be spread at a cost of 2.73 F/kgN, and 40 kg (and not 75) will be transported at a cost of 4 F/kgN. The remaining 35 kgN will be stored in tanks and will be included in the calculation of transport costs for the following year. Hence, though the cost of strategy b for the first year is lower than that of strategy a, it will be higher again the next year because of the stock remaining in the tanks. This behaviour is confirmed for a relatively small excess (below 160 kgN/year). Above this value, spreading proves to be more economical than transport, even when only the transportable slurry is taken into account (multiples of 40 kgN) in transport cost calculations.

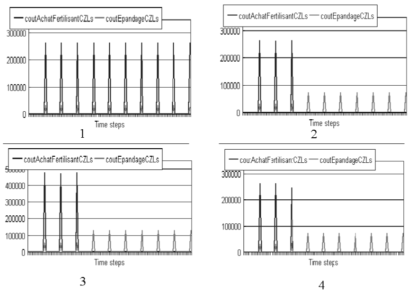

Figure 5: *Cost of nitrogen fertilizer purchase and effluent spreading cost for sugarcane growers for the 4 scenarios.*

spreading outside Grand-Ilet and an adjustment of the spreading limit so as to obtain a balance between environmental pollution (constant and below that of scenario 1) and the cost of effluent management for breeders. This limit would enable all breeders who so wish to dispose of their excess slurry. All those spreading effluent above the legal limit would pay a highly dissuasive pollution charge.

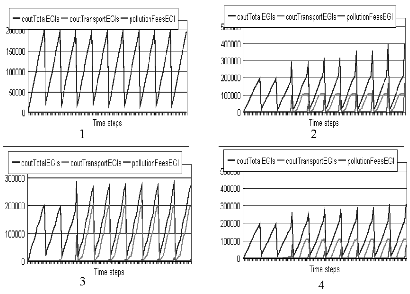

Figure 6: *Effluent spreading and transport costs and pollution charge for all breeders, for the 4 scenarios.*

3 DISCUSSION

The main purpose of our exercise was to use a MAS to illustrate the economic behaviour of pig breeders on Reunion island in the face of changing environmental legislation. In the multi-agent model called Echos, the pig breeders and sugarcane growers are numerous and distributed over a given area with specific characteristics (in this case, distance between agents and nitrogen assimilation capacities). They own farms of different sizes.
The MAS agents act rationally and are well-informed. Their economic behaviour is always determined exclusively by a profit function, that they seek to maximize.
The agents also interact with each other. In our model, their communication capacity is limited, though breeders may spread effluent on neighbouring farms if land is available and, likewise, they may receive their neighbours effluent. Effluent transport to farms in the coastal area is subject to the constraint of sugarcane field availability: if demand for effluent is lower than the annual quantities produced by the Grand Ilet breeders, only a part of the breeders (the first to establish contract with growers) may find a taker for their effluent in the sugarcane zone and hence avoid paying a pollution charge.
The means and practice of transporting slurry to the coastal area are important for defining costs and hence the strategy adopted by agents. In our model, we assume for the moment that each breeder owns a tractor and trailer with a capacity of 10 m^3. Yet for large breeders, this system of transport would require such a large number of journeys that strategy b is systematically ruled out. In future developments, consultations between breeders or even with sugarcane growers could be envisaged to optimize transport and enable them to benefit from the corresponding economies of scale.
The model allows us to couple the nitrogen produced, transported and assimilated by the soil with all economic simulations. This feature of the MAS is very useful for the construction of tools for decision-making and negotiation between players, since the environmental measures are tested not only in terms of economic efficiency and effectiveness, but also in terms of environmental effectiveness.
Thanks to it specific features -dynamic illustration of simulations, simultaneous consideration of economic and ecological variables, spatialized representation of agents and the capacity to make them interact - MAS provide an excellent basis for the creation of decision-making tools to define environmental policy at local level. Compared with economic models based on mathematical optimization techniques, we believe that they are better able to encompass the complexity of the economic, ecological, social and ethical relations involved in the management of environmental impacts.
The validation of MAS models is currently being debated. We believe that their comparison with mathematical models would provide a means to test simulation results. Indeed, we are not claiming that any one approach is superior to the other but believe that the two are complementary, as shown by the present case.
In future developments of the model, we would like to introduce more complex behaviours which differ from one agent to another, as we believe that MAS provide a good means to represent agents possessing limited information and pursuing objectives other than profit maximization alone. The introduction of different strategies in a system of evolutionary games (Weibull, 1995 [17]) should enable us to illustrate the system's response to the introduction of technological or procedural innovations. For example, other alternatives to the transport of slurry to the sugarcane plantations will be introduced, such as the construction of a composting platform or a collective effluent treatment system. Forms of coordination between players will be analysed.

Finally, since we attach a great deal of importance to the ecological dynamics simulated by a model which is basically economic in nature, we intend to improve the methods used to represent the behaviour of nitrogen in the soil (diffusion rates that vary according to the slope and nature of the soil, different types of soil leaching, crop assimilation capacities, etc.).

Appendix

Below we illustrate the cost functions of the players P (sugarcane grower: CZL in the computer program) and S (pig breeder: EGI in the computer program) according to the decision-making rules a (situation in which P and S do not exchange. P buys its fertilizer and S pays charges for any excess effluent it produces) and b (situation in which P receives excess effluent from S, without treatment)

We call:

- p the *fixed* quantity of pollution produced by S;
- $p_1 \geq 0$ the quantity of pollution transferred from S to P;
- τ and p^* respectively the pollution charge and the spreading limit *fixed* by G[(7)];
- C_P the cost function of P;
- C_S the cost function of S;
- $C1_{ep}$, the spreading cost per kg of nitrogen for mineral fertilizer;
- $C2_{ep}$ the spreading cost per kg of nitrogen for pig slurry;
- s_p and s_s are the effluent spreading areas available respectively to P and to S;
- the transport cost, which generally depends on distance;
- d_{PS} the distance between P et S;
- in the model we present, the quantity of fertilizer required by P is proportional to s_p, i.e. αs_p;
- $\Delta p = [p - p^* s_s]$ the excess produced by a breeder with respect to the legal limit.

Rule a**:** if we assume that the unit purchase price for mineral fertilizer is f, then:

$$C_S(p, p^*, s_s, a) = \tau_p [\Delta p]^+ + C2_{ep}\, p \qquad C_P(s_p, a) = f\,\alpha s_p + C1_{ep} \alpha\, s_p \tag{1}$$

where $[\Delta p]^+ = \Delta p$ if $\Delta p > 0$ or 0 if $\Delta p \leq 0$.

Rule b**:** In rule b we assume that P does not make a monetary payment to S for the slurry and that the transport cost is borne by S.
The quantity of slurry to be exchanged ($\bar{p_1}$) is decided by S. The cost function for S is:

$$C_S(p, p^*, s_s, \bar{p_1}, b) = min_{0 \leq p_1 \leq min(\alpha s_p, \Delta p)} C_S(p, p^*, s_s, p_1, b) \tag{2}$$

where :

$$C_S(p, p^*, s_s, p_1, b) = \\ \tau_p [\Delta p - p_1] + C2_{ep} (\min(p, p^* s_s) + \Delta p - p_1) + TC(p_1, d_{PS}) \tag{3}$$

We observe that if $p \leq p^*\ s_s$ then : $\bar{p_1} = 0$.
Hence, the cost function of P is:

$$\begin{aligned} {}_P(s_p, \bar{p_1}, b) &= f\,[\alpha s_p - \bar{p_1}] + C1_{ep}(\alpha s_p - \bar{p_1}) + C2_{ep}\bar{p_1} \\ &= C_P(s_p, a) - (f + C1_{ep} - C2_{ep})\bar{p_1} \end{aligned} \tag{4}$$

When $\bar{p_1} \neq 0$ et $f + C1_{ep} - C2_{ep} > 0$ rule b is preferable to rule a.

Remark .1. *We consider the cost function of S to be a function of p in the case where $TC(p_1, d_{PS}) = h(d_{PS})\, p_1$. In this case:*

$$C_S(p, p^*, s_s, p_1, b) = p_1(h - \tau_p - C2_{ep}) + \tau_p \Delta p + C2_{ep}(\min(p, p^* s_s) + \Delta p)$$

Hence, if: $\tau_p < h - C2_{ep}$ then $C_S(p, p^*, s_s, p_1, b)$ is an increasing function of p_1 and the minimum in (2) is given by $\bar{p_1} = 0$ and if: $\tau_p > h - C2_{ep}$ the minimum is given by: $\bar{p_1} = \Delta p$. We obtain the following expression:

$$C_S(p, p^*, s_s, \bar{p_1}, b) =$$

$$\begin{cases} C2_{ep} p^* s_s + h\,(p - p^* s_s) & \textit{if} \quad \tau_p \geq h - C2_{ep}, \quad p \geq p^* s_s \\ \alpha s_p > \Delta p & \\ \tau_p(\Delta p - \alpha s_p) + C2_{ep}(p - \alpha s_p) + h \alpha s_p & \textit{if} \quad \tau_p \geq h - C2_{ep}, \quad p \geq p^* s_s \\ \alpha s_p \leq \Delta p & \\ \tau_p [p - p^* s_s]^+ + C2_{ep} p & \textit{if} \quad \tau_p \leq h - C2_{ep}, \quad p \geq p^* s_s \\ C2_{ep} p & \textit{if} \quad p \leq p^* s_s \end{cases}$$

(7) In a more advanced version of this model, we will introduce pollution control investment grants.

Remark .2. *We can also consider the case where P pays for $TC(p_1, d_{PS})$, as is sometimes the case in Réunion. In this case, we must study:*

$$C_S(p, p^*, s_s, \bar{p_1}, b) = min_{0 \leq p_1 \leq min(\alpha s_p, \Delta p)} \tau_p [\Delta p - p_1] + C2_{ep} (\min(p, p^* s_s) + \Delta p - p_1) \quad (5)$$

The cost function of P is defined thus:

$$C_P(s_p, \bar{p_1}, b) = f[\alpha s_p - \bar{p_1}] + C1_{ep}(s_p \alpha - \bar{p_1}) + C2_{ep} \bar{p_1} + TC(\bar{p_1}, d_{PS}) \quad (6)$$

Application to the context in Réunion: The introduction into the model of values observed in Reunion makes it possible to construct scenarios based on the economic measures and legal requirements enforced by the public authorities. The examples which follow illustrate the effluent management choice adopted by pig breeders of average size in the Grand Ilet region [(8)] on the assumption of economic rationality and perfect information. Take:

- f = 10 Frs/KgN [(9)];
- α = 150 KgN/ha;
- s_p = 20 ha; s_s = 3ha;
- $C1_{ep}$ = (6.94/150 + 1) Frs/KgN = 1.046 Frs/KgN;
- $C2_{ep}$ = (6.94/4 + 1)Frs/KgN = 2.735 Frs/KgN [(10)];
- p = 1,195.39 KgN [(11)] ;

[(8)] The data illustrated here are taken from a survey performed between 1995 and 1999 in Grand Ilet on Réunion (Cf. Reynaud, 1995 [14] and Renault-Paillat, 1999[13])over a population of 56 pig breeders. This survey shows that the average farm size is 15.17 sows and litters, and that the average surface area of a farm is 3.76 ha, including 1.32 ha of cultivated land, 1.99 ha of fallows and 0.45 ha of buildings (including gardens) (Renault-Paillat, 1999[13]). For sugarcane growers, we took a mean area of 20 ha and a distance from Grand Ilet of 20 km (distance between the coastal zone of St André et and the Cirque de Salazie). The nitrogen fertilizer doses for sugarcane and the fertilizer purchase prices are those given by Uncoopa. The simulated government environmental measures (spreading limits and charges) correspond to possible scenarios and reflect existing or future legislation. The spreading costs are calculated on the basis of surveys performed in Grand Ilet and published by Aubry, Paillat et Guerrin (2001) [2]. Transport costs are taken from Poux et Barbut (1997) [11], quoted by Rainelli and Vermersch (2000) [12].

[(9)] Source Urcoopa.

[(10)] The variable spreading cost is calculated using the methodology proposed by Aubry et al. (2001)[2], which involves adding the costs of labour to the cost of machine operation required to spread one tonne of slurry:
$C_{ep} = [W * PH_0 + T * (PH_t + PH_r)]/Q_M O$
avec:

- PH_0 = 70 Frs/h the hourly labour cost;
- PH_t = 130 Frs/h and PH_r = 50 Frs/hthe hourly cost for the tractor and trailer;
- W et T the time required to perform the operation = 10 min/tank ($6m^3$);
- $Q_M O$ the quantity of organic matter spread (here $6m^3$).

We first transformed these values into costs in F/kgN spread. Then, a proportional cost component that we estimated at around 1 F/kgN of slurry and mineral fertilizer was added to the spreading cost formulas. This component weighs more heavily for mineral fertilizer than for slurry and represents (even if the functional form of costs has no constant corresponding to fixed costs) investments in machines, pits, etc. This term is currently being studied by a survey among breeders in Grand Ilet.

[(11)] To calculate p we consider that a sow and her litters produce 19.7 tonnes/year of effluents and that the average size of a farm is 15.17 sows and litters. Hence, since one tonne of effluents corresponds to 4 kg of nitrogen, p = 15.17 * 19.7 * 4 = 1,195.39 Kg of nitrogen (cf. Renault-Paillat, 1999 [13]).

- p^* = 170 KgN/ha/an;
- Δp = 685.39 KgN;
- TC = 0.77 Frs/tonne of effluent/km;
- d_{PS} = 20 Km;
- We assume that a tonne of slurry contains 4 kg of nitrogen and that a tonne of mineral fertilizer contains 150 kg of nitrogen;
- τ_p is measured in Frs/KgN;

Rule a gives the following costs:

$$C_P(20, a) = 30,000 Frs + 3,,138.8 Frs$$

$$C_S(1,195.39; 170; 3; a) = (\tau_p\, 685.39 + 3,269.39) Frs$$

and:

Rule b**.** Here, remark .1 applies for $TC(p_1, d_{PS}) = 3.85\, p_1$. Hence:

$$C_S(1,195.39; 170; 3; \bar{p_1}; b) = min_{p_1 \leq 685.39}\ p_1(3.85 - \tau_p - 2.735) + \tau_p\, 685.39 + 3,269.3(7)$$

i) if: $\tau_p \geq 1.115$(Frs/KgN) then: $\bar{p_1} = \Delta p = 685.39$. Hence:

$$C_S(1,195.39; 170; 3; 685.39; b) = 4,033.60 Frs,$$

and:
$$C_P(20; 685.39; b) = C_P(20; a) - 5,696.2 Frs.$$

ii) if: $\tau_p < 1.115$ then: $\bar{p_1} = 0$ and we find ourselves in the situation of rule a.

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