Integrated modelling of agricultural production systems–Application to organic waste recycling

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Abstract

Recycling organic wastes in agriculture with controlled environmental impact has become a major stake for sustainable development. With this aim, our research is focused on building computer models for simulating organic wastes management scenarios and assessing their performances against agronomical and environmental criteria. Current achievements and future prospects of this endeavour are described in this presentation.

1 Introduction

1.1 Context and motivations

Improving the sustainability of agriculture has become crucial to deal with tomorrow's challenges such as supplying food to a continuously growing world population while mitigating the environmental impacts. Recycling organic wastes to substitute chemical fertilizers for various organic products is one of the ways towards this end.

Addressing this issue calls for the joint use of heterogeneous knowledge on both the biophysical (i.e. organic products, soils, crops) and managerial (i.e. farmers' practices) components of the whole production systems (single farms or groups of farms). Computer models, integrating various pieces of knowledge, are hence built to represent these systems as linked production and consumption units scattered over a territory. Two modelling approaches have been favoured until now: hybrid dynamical systems, encompassing both continuous and discrete variables, and multi-agent systems.

1.2 Multi-step integrated approach

The driving thread of our research is a multi-step approach yielding successively:

1. Farm surveys, gathering data on the management situations found in the considered territory;

2. Farm typology, characterizing the main farming practices;

3. Conceptual models, synthesizing the knowledge gained from the surveys;

4. Computer models, simulating the interaction between the material flows and the farming practices;

5. Management scenarios assessed against agricultural and environmental criteria;

6. Tools or methods supporting stakeholders management.

Following this approach we developed successively:

- A conceptual representation of organic waste management practices by farmers [3];

- Material flow dynamic simulation models to reason: the management of livestock wastes within single farms [5, 9] or groups of farms [4, 13, 17]; the collective supply of a waste treatment plant [6]; the interaction of farming practices and biophysical flows in dairy farms [19]; the joint individual and collective organization of manure management on a territory [14];

- An explicit representation of human activity at operations level [8].

The agricultural production systems modelling framework integrating the results stemming from this endeavour is presented in §2. Then, examples of actual cases of organic wastes management on territories addressed with simulation models based on this framework are given in §3. Current achievements and future prospects of this research work are finally summarized in the conclusion section §4.

2 Modelling and analyzing material flows on a territory scale

2.1 Conceptual modelling framework

The experience gained with the above cited livestock waste management models (cf. §1.2) allowed us to devise, by generalizing their representational features, an 'Action-Flow-Stock' modelling ontology of agricultural production systems [7]. Although deriving from and mainly applied to issues of waste recycling in agriculture, this ontology has proved useful to deal also with whole-farm simulation modelling [19].

Agricultural production systems are represented as a set of productive units, themselves represented as stocks connected by flows of materials controlled by the farming activities. Two types of flows are distinguished: "workable" flows, which take place only if there is human intervention, and "biophysical" flows, which take place even in the absence of human intervention. These flows interact through human activity, which aims at guiding the biophysical flows by the workable flows it generates. The management of the production system can thus be seen as the control of a set of stocks by the activities of operators (i.e. farmers).

In the specific case of waste recycling, the productive units represented in the system are of two kinds:

- *Production units* (PU) like animal enterprises producing manure, sewage treatment plant producing sludge, land plots producing crop residues, agro-industry producing wastes, etc.;
- *Consumption units* (CU) likely to receive the wastes produced by the PUs, e.g. crops onto which wastes are spread but also storage facilities or treatment plants.

The PUs and CUs linked by the possibilities of waste transfers that may be achieved from the former to the latter by transportation means form a '*configuration*'. Such configurations are then simulated for analysis purposes using simulation models (see examples given in §3).

2.2 Planned vs. situated action

One of the questions that had to be tackled was how to represent farming activities, i.e. human action in agricultural settings. The confrontation of action representation in the models based on our ontology (see §2.1 above) with ontologies devised by other authors (e.g. [10]) led us to question the paradigm of 'planned action' in favour of that of 'situated action' [18]. Altough the classical approach considers action as necessarily based on previously established plans (e.g. see [10]), many studies showed that, actually, most part of human behaviour needs no plan but, rather, stems from continuous local interactions between the agents and their environment.

Our work, still in progress, is thus based on this '*situated action*' paradigm [8, 1, 2]. As our goal is to represent large agricultural systems, basing any action on a plan appeared to us elusive, due to the complexity of both the production systems and the planning process itself. As we want to evaluate production systems, we believe it is by representing as accurately as possible what is 'actually' done, not what 'should' be done, that can allow the impacts of actual activities to be measured. It is, hence, the operational level our models strive to represent, focusing more on action than on decision and planning.

2.3 Assessing farming systems management

We distinguished between two aspects to be assessed in agricultural production systems: their technical performances and their environmental impacts.

In the first case, modelling biophysical flows is needed to simulate their interactions with the workable flows. To do this, the knowledge on the biophysical processes is synthesized by expressions linking as simply as possible the most relevant causes and effects without going into a detailed description of their underlying mechanisms.

In the second case, comparing different management strategies is needed. The issue of sustainable development leads us to think the impacts of these systems in terms of risk on other time and space scales, often larger than those on which they were first considered. Hence, our interest in global assessment approaches, such as life-cycle analysis (LCA), which allows this comparison against different categories of impacts. An example of alternatively combining static LCA assessment with dynamic simulation assessment has been realized [14].

2.4 Management support using models

How to use simulation models to help agricultural stakeholders evaluate and design management strategies calls to practical questions on participatory simulation protocols and tools, likely to facilitate users' learning. Dealing with these questions was first attempted in 2004-2007 [12], unfortunately with too little achievements. Simulation protocols, based on an experimental logic, were set to operate the dynamic simulation models listed above (§1.2).

Although quite used by agronomist colleagues and despite of these attempts, these models, however, have until now never been completely tested in the process to design management strategies with "real" agricultural actors. This failure is mainly due to our poor ability to correctly grasp the social games of players in the organizational or political processes underlying the actual decision processes, particularly at a collective (territory) level. Hopefully, an ongoing project [20] based on a participatory approach involving all kinds of stakeholders may fill this gap soon (see §4).

3 Examples of cases addressed with 'Action-Flow-Stock' models

3.1 Magma: Management of organic wastes in agricultural production systems

The Magma model [5] addresses the case of wastes management within production systems encompassing many PUs and CUs. Two types of productive units are involved in such "distribution" configurations: various enterprises producing wastes (livestock farms, agro-industries,...) and crop plots or waste treatment plants where these wastes are spread over or supplied to. This allows one to account for single farms or agricultural territories with diversified productions, namely joint livestock and cropping production systems.

Taking as input parameters the characteristics of the PUs (manure production flows, storage capacities...), the CUs (cropping areas...), the transportation means (number, payloads, velocities...) and the management rules (fertilization schedules and doses, priorities...), Magma allows one to simulate the time evolutions of PUs' and CUs' stocks, the waste transportation and application activities, as well as indicators of agronomical (amount of manures applied on crops, fertilization indices), logistical (working time, distances travelled...) or environmental (manure stock overflow, crop over fertilization,...) natures.

Magma has been used to analyze waste management policies in livestock farms in Reunion Island[1], such as that described in [15] and, more recently, two cases of periurban market-gardening territories:

- Rufisque (in the suburbs of Dakar, Senegal) encompassing, on the one hand, 180 animal enterprises (horses, cattle, poultry) and agro-industries (fish meal, slaughterhouse, peanut), on the other hand, 580 ha of crops (carrot, cabbage, egg-plant) [13];

[1] Reunion is a French overseas territory in the Indian Ocean close to Mauritius and Madagascar.

- Mahajanga (north-west of Madagascar), encompassing 2 630 animal enterprises (pigs, cattle, sheep, poultry) and 163 market-gardening farms on only 5.6 ha (leaf-vegetables) [17].

In both cases three main scenarios were tested: a base-scenario accounting for the currently observed farmer practices; a tentative scenario where these practices were improved to reduce the overfertilization of crops (in Rufisque) or, on the contrary, to increase the utilization of wastes (in Mahajanga); a prospective scenario where the relocation to remote rural areas of crop (Rufisque) or animal (Mahajanga) farms were simulated to anticipate such decisions likely to be made by local farmers or authorities.

3.2 Approzut: Supply of a treatment plant by multiple farms

The Approzut model [6] was devised to deal with the case of simulating a two-stage production system where the first stage is a set of pig farms producing slurry scattered over a territory and the second is a unique collective treatment plant where slurry is brought in a many-to-one fashion.

Approzut has been used to analyze two cases of pig slurry treatment plant management in Reunion Island:

- one in Grand-Ilet (locality enclosed in a mountainous cirque) involving 51 pig farms adding up to 1 000 sows and producing 20 000 m^3y^{-1} raw slurry where agricultural land was too scarce (<75 ha) to spread it all;
- another in Saint-Joseph (on the South coast) involving 5 pig enterprises (170 sows) and a dairy cattle herd (80 LU).

Based on actual data and stakeholders' preferences, three supply policies were tested: a planned policy with fixed delivery period and delivery size and two reactive policies with time-varying order points and replenishment levels, one based on farm stocks, the other based on the treatment plant stock. The reactive policy focused on farm stocks was judged most adapted to meet the management goals (no stock overflow, robustness) even with random disturbances. In addition to stock management parameters, simulation modelling was able to determine practical implementation parameters necessary in terms of equipement (e.g. how many trucks? which payloads?), labour (workforce? working schedules?) and organization (priority rules to collect slurry according to the size, distance and current slurry stock level of each pig farm).

3.3 Comet: Mixed individual-collective wastes management

Comet [16] essentially results from coupling together the Magma and Approzut models yielding a mixed distribution/supply configuration. It also includes sub-models simulating biophysical processes used as environmental assessment criteria, e.g. the Stal model which simulates ammonia emissions at spreading [11].

Comet has been used to jointly simulate individual manure spreading within 11 single pig farms (adding up to 2 230 sows) and the functioning of a collective spreading plan aimed at transferring manure surpluses from these livestock farms to land loaners in remote 22 crop farms in Brittany (Western France). The alternate use of dynamic simulation with Comet and static life-cycle analysis allowed the whole functioning of this case-study to be thoroughly assessed [14]. This assesment was, this time, not only reduced to logistic and organizational parameters but yielded also environmental impact assessments via the simulation of specific biophysical fluxes, e.g. ammonia and methane emissions at pig slurry storage and spreading. The scenarios tested included the currently observed farming situation and various alternatives involving changes like adaptation of farmers' storage and spreading equipments, covering slurry tanks, reducing the amount of water used in rearing pigs, taking into account soil hydromorphy...

4 Conclusion

4.1 Ongoing projects

Extending the representational power of our action modelling framework based on the situated action theory (see §2.2) is necessary to deal with huge and complex activity systems. Introducing concepts such as agent and space to represent coordination processes as well as the physical structure of work settings is underway [2].

Our farming systems assessment method (see §2.3) also deserves to be rethought in the light of well-defined objectives: what has to be assessed, for which purposes, with which actors, on which space and time scales? Part of this questioning is a perspective currently being addressed by establishing a methodology to assess the impacts and services of organic wastes recycling on a territory scale. This work has been undertaken in the framework of an ongoing project [20] based, since its very beginning, on a participatory approach with the various stakeholders involved in the comprehensive integrated management of organic wastes (agricultural, agro-industrial, urban) in the west coast territory of Reunion Island. Within this project, it is also intended to use models in the collective process of designing and assessing new management options of these wastes. This might, hopefully, finally overcome the limitations pinpointed above (§2.4).

As the extension of model scopes is often sought, in particular to embrace larger territories, the choice of the '*scale of representation*' of a production system becomes also an issue to be addressed, along with model scaling methods.

4.2 Summary

Summarizing, our main achievements are:

1. A methodology for modelling and analyzing material flows on a territory scale;

2. Various simulation models likely to address typical cases of waste management in agricultural production systems;

3. A conceptual modelling framework of farming systems with some degrees of generality;

4. A way of representing human activity in farming systems based on the 'situated action' theory.

However, devising general methodologies for assessing the simulated management scenarios and using models with stakeholders to support actual management practices still remain to be completed.

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