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Participative modelling to help collective decision-making in water allocation and nitrogen pollution: application to the case of the Aveyron-Lère Basin

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Abstract: The aim of this study is to develop simplified tools and methods in collaboration with local stakeholders to facilitate collective decision-making. The project is based on a series of experiments carried out between farmers and environmental officers and researchers (Aquae Project)[1] on the Aveyron-Lère catchment area. Within this framework:

- A model of the catchment area was constructed to examine water consumption and nitrate losses in the area.
- Scenarios were simulated to assess acceptable solutions.

Two types of scenarios were tested with the objective of respecting water allocation and reducing nitrate losses:

1 irrigation and fertilisation optimisation

2 crop rotation management at the level of five areas in the catchment area as well as at whole basin level.

The model allows farmers to assess the cost of various management scenarios of respecting the norms set according to inter-annual climatic variability.

Keywords: participative modelling; collective decision-making; cropping system; pollution; irrigation.

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1 Introduction

Water is one of the most comprehensively regulated areas of the EU environmental legislation. Several programmes and legislations were initiated between 1972 and 2001. Those directives were to be implemented at regional and local levels by the drafting of a set of regulations resulting from negotiations between the different stakeholders involved.

Several studies have attempted to describe and analyse participatory methods (Mendoza and Prabhu, 2005; Rauschmayer and Risse, 2005), which have been regarded as the most appropriate and effective approach to assess agricultural sustainability (Mickwitz *et al.*, 2005; Siebenhüner and Volker, 2005). These methods provide more active roles to stakeholders in the management planning process, and in making decisions about management strategies and their implementation (Haggar *et al.*, 2001; Kuntashula and Mafongoya, 2005). The main criticisms on participatory methods stem from their highly qualitative orientation and their apparent lack of rigour, structure, or systematic procedure for analysing and interpreting stakeholder inputs (Mendoza and Prabhu, 2005). These methods become more difficult to analyse and interpret when different variables involving environment, social and economic approaches and scales are studied. These studies are generally of purely ecological interest when they are carried out on a field scale, or of purely economic interest when analysed on a farm or regional scale (Pacini *et al.*, 2003). The second major limitation of participatory methods is that there are few research tools, which both researchers and farmers can use together to diagnose problems and develop scenarios (Okali *et al.*, 1994).

In this study, the main objective is to develop a methodology based on a participatory approach involving bio-economic models and local stockholders' participation to assess farming sustainability (Siebenhüner and Volker, 2005). Controlling agricultural production, while at the same time respecting environmental constraints, involves a clear understanding of the diversity of farming systems, relationships between their management methods and environmental vulnerability during yield production (Falconer and Hodge, 2001). A range of products are, in fact, available to agricultural managers designed to enable them to manage the states of various environments at different time steps: regionalised technical records, multi-criterion grids to aid decision-making and expert systems. The development of such products brings into play research methods such as surveys, experimentation and modelling (Cretenet, 1995).

Analysis of economic and environmental sustainability of cropping systems involves, by necessity, creating three types of indicators: ecological (soil nitrate, leaching, erosion rates, *etc.*), agronomic via production functions (irrigation, fertilisation, phytosanitary treatments, *etc.*) and economic (farmer's income, *etc.*) (Just and Antle, 1990; Wu and Babcock, 1999). However, given the complexity of the system, the use of these indicators involves creating a 'function', which links production to the environment. This is a major limiting factor for traditional methods based on econometric applications (Antle and Stoorvogel, 2001).

For this reason, the use of bio-economic models, which assimilate both agronomic and economic data, is being increasingly adopted to build a negotiating tool and to take decisions relating to both economic and environmental criteria (Foltz *et al.*, 1995; Barbier and Bergeron, 1999; Flichman and Jacquet, 2003; Flichman, 1997).

The case of the Aveyron-Lère catchment area is a good example of conflict between water resource use and nitrogen pollution. A wide range of agricultural and institutional stakeholders, all defending different interests, is trying to find a solution to the problem of water resource apportionment and its quality maintenance. This basin was selected as the experimental site within the framework.[2]

To analyse cropping system in the Aveyron-Lère (southern France) and to establish the effect of irrigation and fertilisation crop management on water quality and consumption, the variability of the rainfall between years must be considered and should be validated on the scale of the representative farms and whole basin. Hence, it should take into account the variations in the hydrodynamic characteristics of the soil, the cropping choices, and the irrigation and nitrogen fertilisation management methods, which vary according to the climatic years. Once the agricultural system of the basin has been modelled and understood, and relationships between the management methods and the indicators have been analysed, changes will be suggested with the aim of improving the management of the water resource at the whole basin level.

In this paper, the various construction phases of a regional model will be presented:

- definition and validation of the database
- formulation of a typology of the farms in the area to be studied
- generation of unobserved data derived from a biophysical model
- construction of a regional model derived from an agro-economic simulator
- possible scenario testing.

This process allows a wide range of technical and economic data to be obtained for:

- all crops
- all farms both from an individual and a regional point of view.

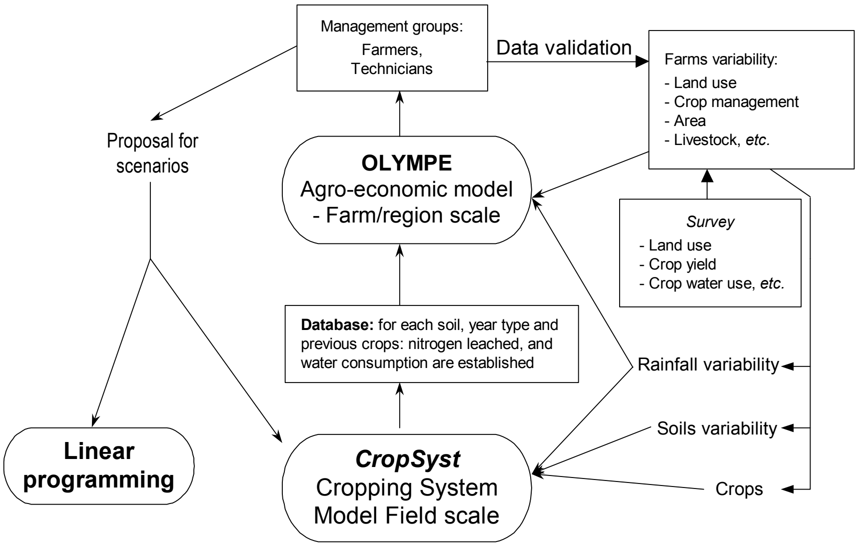
This data is then included in the agro-economic model, which is used both as a database and a simulator (at the individual farm level and at the level of all farms in the area) (Carmona, 2004).

2 Materials and methods

2.1 Methodology

In order to construct a negotiating framework based on the choice of techniques relating to water consumption and nitrogen use, it is necessary to assess the impact of the likely alternatives and to seek negotiable solutions. These likely alternatives are established by using bio-economic models, which represent farming and cropping operations (Figure 1). An agro-economic simulation software package ‘Olympe’ (Attonaty and Soler, 1992; Le Bars *et al.*, 2005) was chosen, which is able to calculate per farm the farmer’s income, water consumption and total quantities of leached nitrogen. This calculation should be computed on the scale of the farms, which are representative of the basin, so that it can be extrapolated at a later stage to the whole basin. Farms should be classified on two levels: (1) initially, from a structural perspective (size, crops, crop management, prices, *etc.*). This data will be collected using primarily regional survey on crop rotation and crop records provided by the farmers’ group; (2) then, from the perspective of the operating procedures on a field scale. The aim is to establish for each crop a production function relating fertilisation and irrigation to the quantities of leached nitrogen and the crop yield. These functions will be established by soil type and climatic year using a CropSyst model.

Figure 1 Model construction process



The construction and the use of the CropSyst and the agro-economic model were conducted in an iterative and interactive (Attonaty *et al.*, 1999) way with the group of farmers and technicians following different levels of analysis and validation. The discussion with the local stockholders was focused mainly on the present:

- Identification of the variables that should be taken into account for analysing the effect of the crop management on yield and nitrogen pollution. The main variables are: soil and climate variability, crop management by year and soil type and the identification of the typology of agriculture production to be representative for the agricultural activity in the Aveyron-Lère Basin.
- Presentation and analysis of the results of the model representing the current situation in a joint meeting.
- Definition of scenarios aimed at reductions in water consumption and nitrogen pollution.
- Simulation of the scenarios under consideration by local stakeholders followed by validation (acceptance) or rejection of the results obtained.

2.2 Agronomic modelling: use of CropSyst

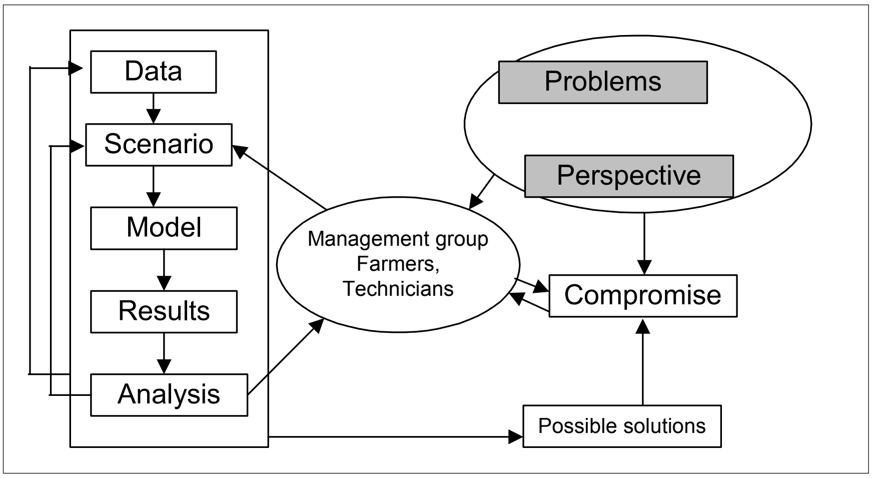
The CropSyst model is a partially mechanistic model, which attempts to reproduce soil and plant operations in a dynamic way based on the known laws of biology and physics or on empirical relationships based on climate and cropping methods. It was developed for a wide variety of species grown around the world: wheat, corn, sorghum, millet, barley, oats, alfalfa, potatoes, vines, *etc.* CropSyst operates on daily time steps. The crop growth cycle is divided into several successive development phases, each with its own parameters to assess growth rate and assimilate allocation based on genetic, edaphic and environmental factors. During each of these phases, limiting factors (hydrous deficit, nitrogenised nutrition, *etc.*) are introduced as reducing functions of the basic growth model.

2.3 Agro-economic modelling: use of Olympe

The Olympe software[3] (Le Bars *et al.*, 2005) will build into its model economic and technical aspects (crop management) of the farms' operations as well as externalities (nitrate leaching).

By modelling on Olympe, the consequences of the different scenarios under consideration by the farmer or the authorities can be forecasted (Figure 2). Thus, using a model which simulates the consequences of certain aspects of its management puts it in a situation where it can learn and modify or confirm its decision parameters. Consequently, it can evaluate the relevance of its parameters with regard to its projects and the future development of the farm it is involved with.

Figure 2 Modelling under Olympe and co-construction of the model



This tool allows us:

- To obtain a database on operating systems.
- To evaluate the consequences of investing in, getting rid of, or adding an input/output per crop, a change in a crop schedule, a change in crop management, *etc.*
- To build into the simulation unknown factors and to assess the consequences of unforeseen events, which can be internal or external to the company, on the results of the project (price fluctuations, climatic factors, changing market trends).

Olympe allows groups of farms to be constructed by a matrix of farmer numbers linked to a type of farmer (cf. typology). The simulator acts by highlighting the impact of changes on the crops or management methods but does not allow the strategies and courses of action of the various stakeholders to be represented. In order to model the complete operation of the system, it is imperative to understand and formalise the stakeholders' rules for decision-making as well as the laws which govern these rules. Olympe was designed to work interactively with farmers, either individually or as a group.

3 Application

3.1 Presentation of the study area

The 'Aveyron – Lère downstream' basin (60.000 ha cultivated and 80% of global water consumption for farming in average year) is situated in Tarn-Garonne district (South West, France) (AQUALIS *et al.*, 1997; AGRESTE, 2002). The climate is characterised by significant variations in inter-annual precipitation, which have led to a considerable increase in irrigation. The landscape of the area is composed of three different soil types. For these reasons, the basin was divided into five natural regions, each one with its particular soil type and water supply, and as a consequence, different cropping systems. All the representative choices and the data used in the modelling process were discussed and validated by a farmers' group comprising of farmers and technicians.

The average surface area of the farms was 30 ha in 1997, with a trend towards a reduction in farm numbers and an increase in size. As for the activities, which have been developed, the heterogeneous nature of the area's soil has resulted in varying farming activities and crop diversification patterns. In this area, farms tend to specialise in fruit and cereal production. The surface of irrigated land across the area has constantly increased, accounting for 35% of the Useful Agricultural Area (UAA) in 1997, with an average irrigable area per farm of 18.7 ha. The irrigated areas in this zone are divided between corn grown for seed and silage (a major consumer, which single-handedly accounts for almost two-thirds of the irrigated area), sorghum, soya, sunflowers, fruit and vegetable production in open country (AQUALIS *et al.*, 1997; Menon, 2000; Majhoubi, 2002).

3.2 The different stages in building the regional model

The process involves the following phases (Le Grusse, 2001):

- Database

  Documentation used to draw up the Aveyron – Lère downstream river contract was consulted. This contract contains information on the physical characteristics of the hydrosystem, usage, as well as a summary of the key issues and ways forward, such as those identified during a forecasting workshop, assembling 70 stakeholders with vested interests in the management of the catchment area (local elected representatives, officials, communities, associations, *etc.*) (Batut, 2001).

  A regional survey of 2000 detailed rotation records of 1700 farms in the area was used. This database was completed, with the collaboration of local farmers and technicians, by associating each crop by soil and rainfall, types of yield and crop management (mainly the amount of water and nitrogen).

- Building a farm typology

  Given the large number of farms (1700), a typology was formulated based on data analysis techniques and classification. This typology was discussed, amended and validated by the farmers' group during meetings. For each group, five areas were chosen, corresponding to the five natural areas (specific soils and water resources), which were described for the catchment area. Three types of different soils are present in these areas (*terrefort*, *alluvions* and *boulbène*), giving different yields and pollution rates. The production systems were also classified into five categories according to size. For each class-category-area combination, the farm with an area closest to the group average was taken as the representative farm. The number of possible combinations is: No. of classes × No. of categories × No. of areas = 500 possible groups. Given that certain groups are void, 296 representative farms were obtained, which characterise the types of farms in the catchment area. In order to build the model of the basin, the detailed data of these 296 farms was entered. Then the data was weighted with a coefficient equal to the total number of farms that each one represents to obtain results at the regional level. This task of formulating the typology, choosing areas and stratification was carried out with the farmers' group. Each item of data was validated during monthly meetings running over the course of a year. This process enabled the data to be structured but also provided a learning experience for the farmers' group, which was able to adapt the representation model to their own set of circumstances.

- Building a tested scenario: to reduce water consumption and nitrogen pollution, two types of solutions were chosen after negotiation and discussion with local stockholders:

  1. Scenario 1 'optimal management, fixed rotation'

     A better estimation of the water and nitrogen crop needs. This objective is reached by using the crop model for each type of soil, and rainfall variability and rotation, without changing the crop rotation.

  2. Scenario 2 'current management, optimal rotation'

     A better selection of the crops which return the maximum overall income while respecting a series of constraints and creating specific zones for all kinds of crops. These constraints are related to agronomy, the market, water consumption and nitrate leaching. Based on this methodology, the main constraint was to reduce water consumption compared to current situation. To attempt this objective, a linear programming model was used.

- Building an agro-economic simulation model

  The model which represents the basin's farming activities by weighting average farms by size category, soil types and geographical area. This model is developed using Olympe software, by which different management scenarios can be tested and their effects can be assessed on the economic results and on the environment for the different climatic situations and the different soils.

- Simulation of the scenarios suggested by the farmers' group with Olympe

  The objective was to reduce water consumption and nitrate leaching at the regional level. (Solutions suggested by the stakeholders or originating from an optimisation model under constraints.)

3.3 Parameter setting and validation of the agronomic model

3.3.1 Hypotheses

The CropSyst model is applied to a system, which is defined by a parallelepiped of soil. This generally corresponds to one hectare in size and is considered to be a porous environment of horizontally uniform properties and keeps its shape. The system could also be stratified in several layers of distinct properties. In all cases, it is delimited at the top by the soil (or plant)-atmosphere interface and at the bottom by a plan, parallel to the surface beyond which percolated water reaches the watertable. The upper part of this system is represented by a crop or an unworked fallow, which acts on the soil and is subjected at the same time to the soil's effect. Studying this system via modelling gives rise to a whole range of hypotheses:

- The soil water budget operating in each system is not influenced by the adjacent system.
- The hydrodynamic characteristics of the soil are assumed to be constant and do not change when the soil is worked.
- Plant growth can only be influenced by the following factors: temperature, light above the crop, soil water and nitrate.
- Vegetation coverage is assumed homogeneous.
- The effects of weeds and diseases are not taken into account by the model.

3.3.2 Choice of the representative fields

In this study, the system to be modelled is represented by associating three elements: soil, plant and climate units. By assuming that precipitation is homogeneous in the area, the system can be reduced to the soil-plant association for a given year. Existing literature, surveys with farmers and the farmers' group enabled us to determine the representative fields at the level of the catchment area. The most common soils to be found at the level of the study area are:

- Terrefort

  These soils have a clay-soil texture and are relatively compact, prone to erosion and more suited to fruit trees and field crops (Revel, 1982).
- Alluvions

  These soils have a dandy-loam texture and are deep-lying, permeable, easy to work on but with low water-retention (INRA, 1970).
- Boulbène

  These soils have a clay-loam texture. They are found on the old terraces of Aveyron and are characterised by soil, which is low in organic matter with low water-retention (INRA, 1989).

3.3.3 Parameter setting and validation of the agronomic model

The aim is to produce a model, which can reproduce each crop operation adequately. This involves setting the model's parameters for each crop, soil type and climate. Calibrating the model requires the adjustment of certain parameters within a reasonable range of fluctuation, which have already been defined and identified by previous research, scientific data or experiments undertaken in the same area of study (Belhouchette, 2004). According to this principle, only a small number of parameters were calibrated by minimising the difference between observed and simulated biomass. Thus, two parameters were selected to carry out the model's parameterisation and are included in the estimation of total dry matter: 'biomass-transpiration, K_{BT}', 'Radiation use efficiency, K_{LB}' and LAImax coefficient.

Parameters were set by adjusting simulated biomass with observed biomass over an average year. Subsequently, validation was carried out by comparing simulated biomass with that established by the farmers' group during dry and wet years (Tables 1 and 2).

Table 1 Model validation. Simulated yield vs. observed yield for all soil types and for the average year

	Observed yield (kg/ha)	*Simulated yield (kg/ha)*	*Difference (%)*
Durum wheat			
Terrefort	5000	5321	–6.0
Alluvion	5000	5991	–16.5
Common wheat			
Terrefort	6500	6877	–5.5
Alluvion	6500	7027	–7.5
Grain maize			
Terrefort	9000	9380	–4.1
Alluvion	11 000	10 161	8.3
Boulbène	10 000	8925	12.1
Maize seed			
Terrefort	2950	2946	0.1
Alluvion	3000	3560	15.7
Boulbène	3000	3392	–11.6
Dry sorghum			
Terrefort	7500	7476	0.3
Alluvion	7500	8705	–13.8
Boulbène	5000	6127	–18.4
Irrigated sorghum			
Terrefort	8000	8287	–3.5
Alluvion	8000	9944	–19.6
Boulbène	7000	6408	9.2
Sunflower			
Terrefort	2000	2273	–12.0
Alluvion	2000	2541	–21.3
Boulbène	1700	2205	–22.9
Irrigated sunflower			
Terrefort	2040	2026	0.7
Alluvion	2120	2107	0.6
Boulbène	1600	1571	0.5

Table 2 Model validation. Simulated yield vs. observed yield for all soil types and for wet and dry years

	Year	*Observed yield (kg/ha)*	*Simulated yield (kg/ha)*	*Difference (%)*
Durum wheat				
Terrefort	Wet	6000	6634	–11.0
Terrefort	Dries	4000	2993	25.0
Alluvion	Wet	6000	6634	–11.0
Alluvion	Dries	4000	3922	2.0
Common wheat				
Terrefort	Wet	8000	7322	8.5
Terrefort	Dries	6500	3738	42.5
Alluvion	Wet	8000	7320	8.5
Alluvion	Dries	6500	4947	23.9
Grain maize				
Terrefort	Wet	9000	10 512	–16.8
Terrefort	Dries	9000	7703	14.4
Alluvion	Wet	11 000	11 019	–0.2
Alluvion	Dries	11 000	8873	19.3
Boulbène	Wet	10 000	9615	3.8
Boulbène	Dries	10 000	8043	19.6
Maize seed				
Terrefort	Wet	3000	3197	–6.6
Terrefort	Dries	2900	2074	28.5
Alluvion	Wet	3000	3746	–24.9
Alluvion	Dries	2900	2333	19.5
Boulbène	Wet	3000	3648	–21.6
Boulbène	Dries	2900	2218	23.5
Dry sorghum				
Terrefort	Wet	10 000	9245	7.5
Terrefort	Dries	5000	4077	18.5
Alluvion	Wet	10 000	9979	0.2
Alluvion	Dries	5000	5230	–4.6
Boulbène	Wet	9000	7132	20.7
Boulbène	Dries	3500	3165	9.6

Table 2 Model validation. Simulated yield vs. observed yield for all soil types and for wet and dry years (continued)

	Year	*Observed yield (kg/ha)*	*Simulated yield (kg/ha)*	*Difference (%)*
Irrigated sorghum				
Terrefort	Wet	10 000	9794	2.0
Terrefort	Dries	6000	6026	–0.4
Alluvion	Wet	10 000	9879	1.2
Alluvion	Dries	6000	7133	–18.9
Boulbène	Wet	9000	6711	25.4
Boulbène	Dries	5000	5468	–9.3
Sunflower				
Terrefort	Wet	3000	2882	3.9
Terrefort	Dries	1500	1964	–30.9
Alluvion	Wet	3000	2856	4.8
Alluvion	Dries	1500	2047	36.5
Boulbène	Wet	2500	2888	–15.5
Boulbène	Dries	1500	1767	–17.8
Irrigated sunflower				
Terrefort	Wet	2018	2020	–0.1
Terrefort	Dries	1740	1746	–0.5
Alluvion	Wet	2065	2060	0.1
Alluvion	Dries	1700	1701	–0.3
Boulbène	Wet	1600	1702	–6.2
Boulbène	Dries	1300	1400	–7.7

The tables show a close correlation between the yields simulated by CropSyst and those established by the farmers' group. With the model configured to the local conditions of the catchment area, it is used to build a database containing a yield, a quantity of leached nitrate, a final stock of nitrate in the soil and an optimal irrigation dose for each crop type, soil type, climatic year type, and irrigation and nitrogen fertilisation doses.

4 Simulations and results

A regional model was developed following validation meetings of the data and the representation models. Interactive user sessions of the model were then set up. The model could be seen by everyone with the help of a video projector.

First of all, stakeholders used the model as an analytical tool of the current situations at different levels and on different aspects: the extent of water demand for different farmer types, pollution by nitrates and the resulting economic surplus. This was cross-referenced by soil and climate type. The model serves to reveal the actual situation at the regional level. Each local stakeholder has, at the outset, only a partial vision of the actual situation, with little knowledge of the other production systems, their water consumption, their share of nitrate pollution and their economic significance at the regional level. The aim of these sessions is to reduce information asymmetry and to build a single collective representation.

Once the information has been shared and discussed, the second user phase of the model can begin. Subsequent sessions are dedicated to the interactive use of the model as a forecasting tool. The objective is to forecast, with stakeholders, possible scenarios where agricultural production systems might evolve in the region and to measure the impact in terms of water demand, nitrate pollution and economic results. Using the model, rotations can be modified at the level of farming systems or area. Furthermore, changes can be made to crop management, and yields and prices can be varied.

The model was designed to be used interactively, promoting discussion between stakeholders and opening up a dialogue, thus leading to negotiations. Following these discussions, the selected scenarios are then fine-tuned and the results are presented in subsequent meetings where new variants can be introduced with immediate effect (Attonaty and Le Grusse, 1994).

4.1 The result of the first scenario: optimal management, fixed rotation

Based on the results generated by CropSyst, the optimal quantities of nitrates required by the principal crops were defined. For the irrigated crops, it was also attempted – without reducing yields – to determine water amounts and an optimum irrigation schedule for each soil type and each year type. The procedure consisted of simulating the chosen crops with varying increasing doses of nitrogen and water. For each nitrogen amount, the crop yield and leaching for each soil type and year type are obtained. This data generated the crop yield response curves to fertilisation and irrigation (Figures 3–4). These curves enable us to define the optimal amounts of nitrogen and water (Table 3). The generated database was incorporated in the agro-economic model and will allow them to be compared with the pollution generated by the farmers when they apply their own doses. The result of the first scenario demonstrated that it is possible to achieve a reduction in water consumption together with a reduction in nitrates leaching (Bel *et al.*, 1999; Benslimane, 1999) without changing crop rotations, as a result of changes in production management (water, nitrates) (Table 4). This gain does not occur uniformly across the area or for all production classes. Variability is also significant in relation to the climatic year type. Thus, the reduction in water consumption and nitrates leaching occurs primarily in ‘alluvions and boulbène’ areas, where variations are considerable according to the year type compared with current consumption. Moreover, the suggested crop management techniques produce an increase in income compared with the current situation. This is a consequence of the entrant level, matching crop requirements more closely. Even if this scenario represents an optimal situation, which is difficult to achieve in reality, it demonstrates at least that there is room for manoeuvre, which will lead to reductions in water consumption, pollution and costs, while maintaining the same yields in certain types of soils and certain production systems. Thus, recommendations can be made and quantifiable priorities can be defined.

Figure 3 Yield variation of grain maize in relation to the amount of nitrogen fertilisation and irrigation volume chosen by the model for each nitrogen dose

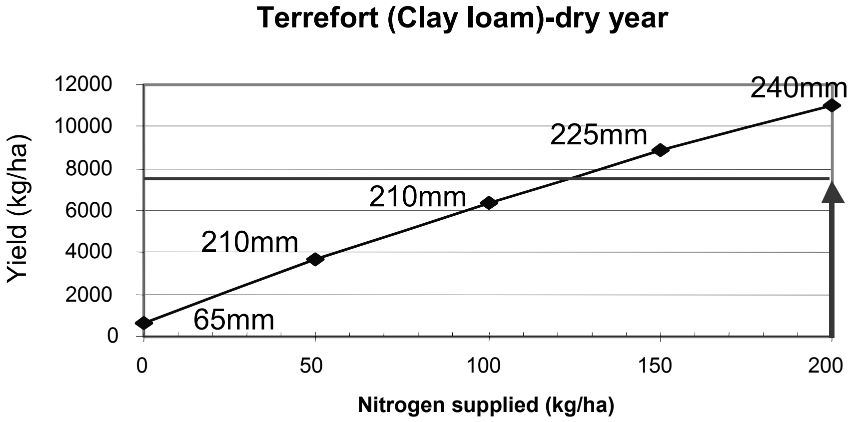


Figure 4 Leaching variation of grain maize in relation to the amount of nitrogen fertilisation and irrigation volume chosen by the model for each nitrogen dose

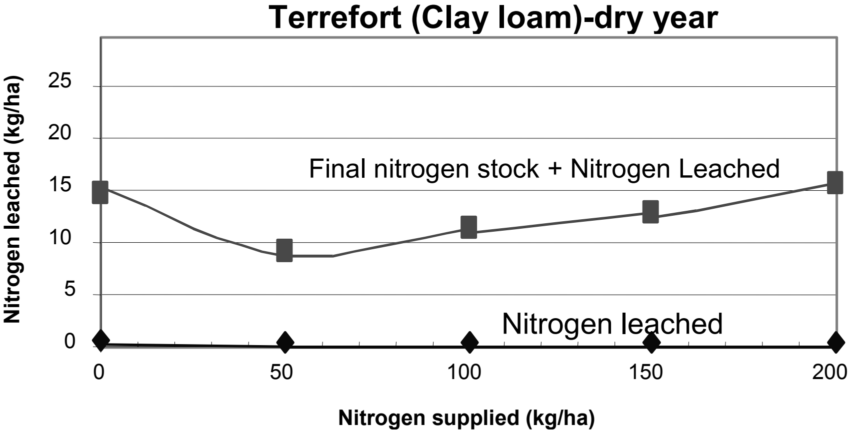


Table 3 Example of yield, irrigation, nitrate fertilisation, nitrate leached and crop income for the maize grain crop (Cropsyst and Olympe results).

		Real crop management					*Optimal crop management*				
Soil	*Years*	*Yield (kg/ha)*	*Irrigation (m3/ha)*	*N (kg/ha)*	*Leaching (kg/ha)*	*Income (euros)*	*Yield (kg/ha)*	*Irrigation (m3/ha)*	*N (kg/ha)*	*Leaching (kg/ha)*	*Income (euros)*
Terrefort	Yet	10 512	700	200	19.7	785	10 512	700	181	17.9	795
	Average	9380	1400	200	24.1	614	9380	1400	155	19.0	638
	dry	7703	2000	200	22.18	395	7703	2000	127	37.0	433
Alluvions	Yet	11 019	900	200	22.8	822	11 240	700	200	11.7	860
	Average	10 161	2000	200	25.5	649	11 574	1500	200	18.4	834
	dry	8873	2750	200	27.8	459	8686	2250	150	11.6	504
Boulbène	Yet	9615	12 000	200	48.0	654	11 007	900	200	24.0	821
	Average	8925	2500	200	28.5	483	8888	1600	150	18.3	575
	dry	8043	4000	200	20.6	277	8335	2780	150	12.5	427

Notes: Data for real management and optimal data are respectively obtained from stockholders consultation and CropSyst model. To attempt the maximal yield, farmers applied the same amount of nitrogen fertilisation independently of the type of the soil or weather.

Table 4 Difference (%) between the total: water, nitrate applied, nitrate leached and income respectively established from survey (current farmers' management: base situation) and from the scenario 'optimal management, fixed rotation'.

	Water			*Applied nitrate*			*Nitrate leached*			*Income*		
	Dry	*Average*	*Wet*	*Dry*	*Average*	*Wet*	*Dry*	*Average*	*Wet*	*Dry*	*Average*	*Wet*
Z 1	–11.4	–14.3	–17.9	9.9	1.4	1.4	71.4	8.9	4.0	–0.4	–0.0	–0.1
Z 2	–13.9	–20.6	–17.8	22.4	5.7	5.7	95.0	51.3	21.0	–0.4	–0.2	–2.0
Z 3	–23.4	–12.1	–16.6	18.3	4.7	4.7	96.1	65.0	17.8	–7.2	–5.9	–1.5
Z 4	–22.2	–22.9	–13.4	16.8	4.5	4.5	94.1	68.8	41.2	–21.9	–14.5	–10.3
Z 5	–8.8	–11.8	–11.9	23.6	6.8	6.8	95.0	43.5	17.0	–1.5	–0.3	–2.9

Note: Results were aggregated at area (Z) level using the 'Olympe' model

4.2 The result of the second scenario: current management, optimal rotation

With the assistance of a linear programming model, rotations were optimised by selecting those which return the maximum overall income while respecting a series of constraints. These constraints are related to agronomy, the market, water consumption and nitrate leaching. For each of the five areas of the basin a system of equations was devised, which shows the contribution of each crop at the levels of income, water consumption and total nitrate leaching. For a given year type, overall income will be defined as the sum of the individual incomes of the existing crops. To take account of climatic variability, decisions on crop rotation should be taken in relation to a single income function, which considers the income of the different year types with the probability of them occurring (Dry year: 0.18; Average year: 0.68; Wet year: 0.14). The objective function for a given area is defined as follows:

$$M_T = 0.18 * (\Sigma S_i * M_{is}) + 0.68 * (\Sigma S_i * M_{im}) + 0.14 * (\Sigma S_i * M_{ih})$$

with M_T = total income (F); S_i = crop area i (ha); M_{is} = crop income *i* in a dry year (F/ha); M_{im} = crop income *i* in an average year (F/ha); M_{ih} = crop income *i* in a wet year (F/ha).

Based on this function, two new constraints are:

1 the quantity of available water is limited to 2000 m^3/ha

2 nitrogen pollution will be reduced by 20% compared with actual pollution (Table 5).

Table 5 Difference (%) between the total: water, nitrate leached and income respectively established from survey (current farmers' management) and from the scenario 'current management, optimal rotation' by model optimisation at area (Z) level

	Water			*Nitrate leached*			*Income*		
	Dry	*Average*	*Wet*	*Dry*	*Average*	*Wet*	*Dry*	*Average*	*Wet*
Z 1	6.5	3.7	–4.9	46.4	26.4	20.0	–3.7	–1.0	4.4
Z 2	–1.3	–1.6	–2.2	62.4	20.0	23.7	–12.2	–9.4	–5.5
Z 3	9.6	11.7	9.9	69.8	54.8	28.7	–20.1	–23.6	–23.3
Z 4	29.6	28.9	26.7	73.5	41.4	24.9	–24.5	–23.8	–21.2
Z 5	–2.7	–3.4	–4.7	20.0	20.0	20.0	–2.2	–2.0	–0.2

In order to gain a regional perspective, an overall objective function was formulated, based on the objective functions defined by the area. The same constraints were applied to this function, as to the previous ones. Figures 5 and 6 show the results for area and regional scale optimisations. For the two optimisation cases, lower water consumptions were achieved, than current ones. In dry years, water consumption varies from 28 million m^3 to 21 million m^3 in the optimisation by area type, compared with 22 million m^3 in the optimisation case at the overall level.

Figure 5 Comparison between total water consumption per optimised crops at basin level in the present situation, after optimisation per area and after regional optimisation, for the three possible climatic year types

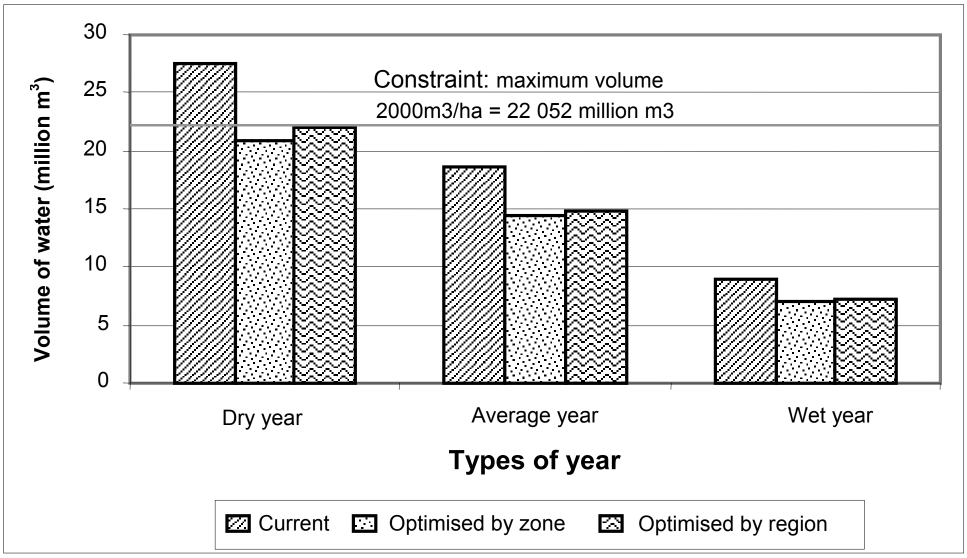
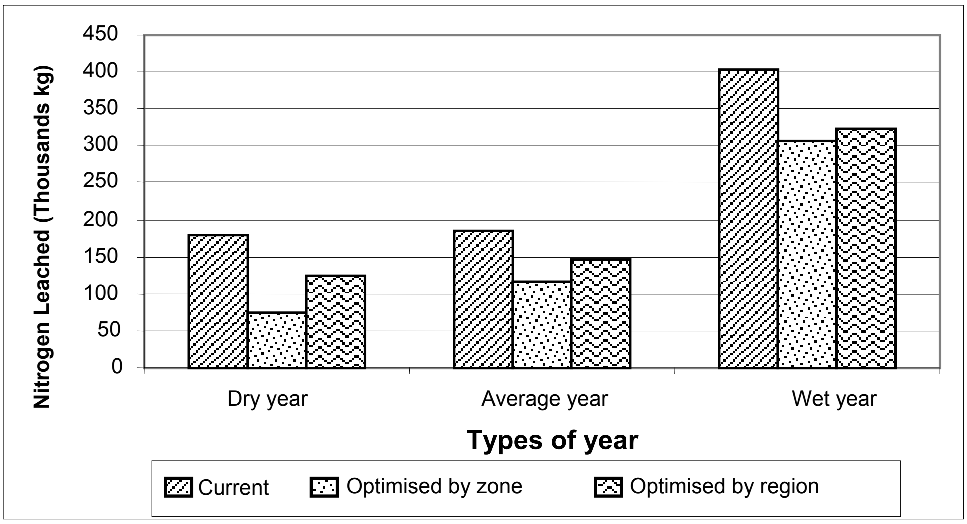


Figure 6 Comparison between total nitrate leaching per optimised crops at basin level in the present situation, after optimisation per area and after regional optimisation, for the three possible climatic year types



For the two models, the reduction in water consumption is greatest in dry years. When the results are compared for leaching, as for water consumption, it can be seen that leaching is reduced in the two models below the level which was imposed as a constraint. This reduction is also greater in the optimisation model per area, but the difference is much smaller than for the water volumes, especially in dry and wet years.

A comparison of the total regional income (Table 6), which is presently achieved, with the income derived from each optimisation model, highlights the economic impact which could be achieved by adopting the new crop rotations (Tables 7–9). The model, optimised by area, affords the greatest reductions in water consumption and leaching. The reduction in income is also greater than in the model optimised at the regional level (94 Euros/ha compared with 30 Euros/ha). Income optimisation across the whole of the region allows an acceptable solution to be achieved from an environmental perspective (as it respects the imposed constraints, as it does in the solution which is optimised by area) with a much lower economic impact (Figure 7). Nevertheless, reductions in water consumption and leaching are not evenly distributed across all areas of production.

Table 6 Difference (%) between total: water, nitrate leached and income respectively established from survey (current farmers' management) and 'current management, optimal rotation' by model optimisation at region level

	Water			*Nitrate leached*			*Income*		
	Dry	*Average*	*Wet*	*Dry*	*Average*	*Wet*	*Dry*	*Average*	*Wet*
Z 1	57.7	56.9	54.1	52.0	28.8	15.0	–11.5	–0.1	8.8
Z 2	9.7	10.7	10.6	85.0	23.9	25.9	–19.4	–13.4	–7.3
Z 3	–0.1	–0.1	0.1	6.7	8.4	19.2	–0.1	0.1	0.1
Z 4	14.9	14.8	13.8	13.6	24.0	19.1	1.4	5.1	8.5
Z 5	14.7	15.8	15.7	24.3	23.2	17.8	–7.1	–2.4	1.7
Region	10.6	11.3	10.9	31.2	20.7	20.0	–8.1	–4.0	–0.1

Table 7 Cultivated main surfaces for each type of crop aggregates at regional level: actual situation with current water and nitrate farmers' management

Cultivation (ha)	*DW*	*CW*	*GM*	*MS*	*DS*	*IS*	*S*	*IS*	*Total (ha)*	*Income (euros)*	*Income/ ha*
Z 1	46	720	252	6	374	76	238	0	1712	1 076 342	629
Z 2	56	2308	2033	477	715	1119	1143	2	7853	5 839 805	744
Z 3	60	872	1441	436	202	222	664	28	3925	3 539 223	902
Z 4	46	677	2429	454	73	189	544	35	4447	3 206 250	721
Z 5	773	1281	1333	279	86	128	1096	87	5063	3 658 218	723
Total	981	5858	7488	1652	1450	1734	3685	152	23 000	17 319 837	753

Notes: DW: Durum Wheat
CW: Common Wheat
GM: Grain Maize
MS: Maize Seed
DS: Dry Sorghum
IS: Irrigated Sorghum
S: Dry Sunflower
IS: Irrigated Sunflower

Table 8 Cultivated main surfaces for each type of crop aggregates at regional level: established by model optimisation at area (Z) level

Cultivation (ha)	*DW*	*CW*	*GM*	*MS*	*DS*	*IS*	*DS*	*IS*	*Total (ha)*	*Income (euros)*	*Income/ ha*
Z 1	0	511	235	6	586	5	295	75	1713	1 072 580	627
Z 2	100	1492	2458	120	1458	1096	1064	64	7852	5 307 447	676
Z 3	100	447	1450	49	978	65	788	47	3924	2 724 069	694
Z 4	100	442	1500	54	1407	0	945	0	4448	2 453 371	552
Z 5	342	1112	1427	279	471	48	1185	200	5064	3 595 026	710
Total	642	4004	7070	508	4900	1214	4277	386	23 001	15 152 492	659

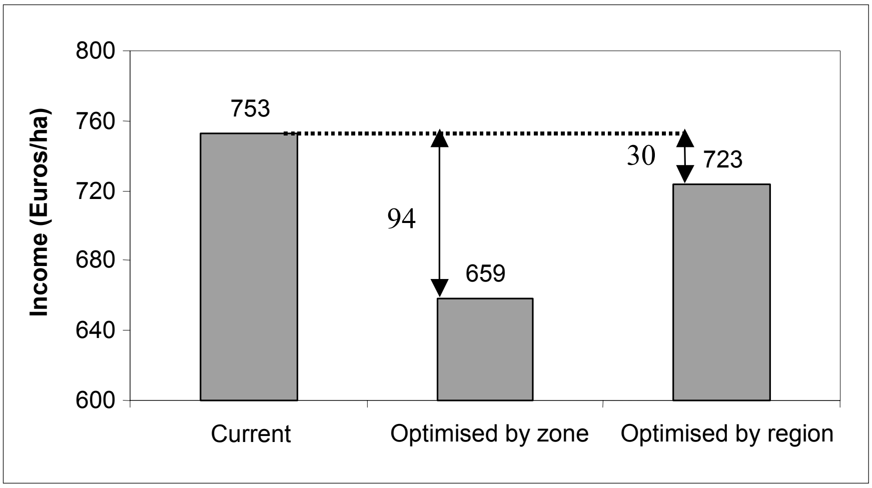
Notes: DW: Durum Wheat
CW: Common Wheat
GM: Grain Maize
MS: Maize Seed
DS: Dry Sorghum
IS: Irrigated Sorghum
S: Dry Sunflower
IS: Irrigated Sunflower

Table 9 Cultivated main surfaces for each type of crop aggregates at regional level: established by model optimisation at regional level

Cultivation (ha)	*DW*	*CW*	*GM*	*MS*	*DS*	*IS*	*DS*	*IS*	*Total (ha)*	*Income (euros)*	*Income/ ha*
Z 1	0	511	51	6	768	0	376	0	1712	1 078 784	630
Z 2	100	1492	2050	0	1930	915	1366	0	7853	5 072 297	646
Z 3	0	547	1450	409	692	263	539	24	3924	3 539 540	902
Z 4	0	542	1750	500	881	0	774	0	4447	3 370 576	758
Z 5	269	1185	921	279	865	0	1544	0	5063	3 573 759	706
Total	369	4278	6222	1194	5136	1178	4599	24	22 999	16 634 957	723

Notes: DW: Durum Wheat
CW: Common Wheat
GM: Grain Maize
MS: Maize Seed
DS: Dry Sorghum
IS: Irrigated Sorghum
S: Dry Sunflower
IS: Irrigated Sunflower

Figure 7 Comparison between total income (aggregated income, which takes into account the income for each climatic year type and the probability of it occurring) at the basin level linked to the crops considered in the optimisation in the present situation, after optimisation by area and after regional optimisation



The results of Scenario 2 demonstrate that water consumption and nitrate leaching at the regional level can be reduced through crop area redistribution, while still respecting the agronomic and market constraints, which affect production in the region (Table 5). This reduction in water consumption and nitrate leaching primarily affects the areas where the most critical values can be found at the present time. The reduction in consumption and leaching will result in a drop in gross income. This drop is much smaller when an optimisation by area is carried out, which takes into account the constraints of water and nitrate leaching across the whole area. This shows that in the quest for an optimum result with common objectives, it is possible to achieve a better solution through negotiation, in particular, when possible territory-wide measures are considered. This approach could be used to help stakeholders build the local action programme required by the European Nitrates Directive to reduce, in vulnerable zones, pollution caused by nitrates.

5 Discussion and conclusions

The aim of this study was to construct a representation system of the agricultural production systems on a given catchment area with a group of farmers. By simulating alternative solutions, this system should help stakeholders to negotiate the management of the demand for agricultural water and of diffuse nitrate pollution.

An operating model of the basin's agricultural system was thus used, in particular, to highlight the changing trends in water consumption and the interactions between the different production areas. Based on the first results obtained, the model was calibrated and validated by the stakeholders (farmers' group). This allowed different scenarios to be assessed and tested.

The basin model consists of the combined application of a bio-physical model of cropping operations and an agro-economic model of an agricultural company's operations. The two models complement each other by establishing the link between the physical and economic system, as well as between crop production techniques and environmental impacts. Using this system, changes were tested, which resulted in reductions in water consumption and nitrate pollution. The initial results of the model (with field data), led us to note that the heterogeneity of the basin's soils and crops causes variations in water consumption and quantities of leached nitrate. This irregular crop behaviour by area gives rise to heterogeneous economic results. In order to test scenarios, it will be necessary to take this diversity into account, bearing in mind that each area of production will have its own response to the proposed changes.

By modelling the system, the impact of changes in crop rotations and farming techniques can be assessed, both from an economic (farmers' income) as well as an environmental perspective (water consumption, pollution), while taking account of climate and soil variations.

The aim of this study is to start a dialogue between stakeholders by holding discussions on the results obtained in simulations. Thus, joint solutions can be found, and all parties can feel satisfied with the outcome. Training sessions in negotiating skills could be organised in the form of simulation games with all stakeholders involved (Allaya *et al.*, 2004; Le Bars *et al.*, 2004).

By constructing an operating model of basin agriculture and presenting the scenarios:

- The extent of farming's role in conflicts has been demonstrated. This activity consumes the highest proportion of resources (80% of total water consumption in the basin) and, as a result, contributes to water pollution through nitrate leaching.
- It has also been shown that it is possible to reduce this water consumption and nitrate leaching by changing cultivation methods or crop rotations.
- As researchers, we applied our tools and expertise to try to facilitate negotiations between the stakeholders in this conflict over resource use: Constructing the model helped to start a debate, by promoting joint meetings and a process of dialogue.
- It is yet impossible to state whether an agreement will be reached between stakeholders to resolve the problems of water resource apportionment and to halt water quality deterioration in the Aveyron – Lère catchment area.

However, it has been shown that alternative production techniques and crop rotation systems can be explored with a view of improving resource management both in quantitative as well as in qualitative terms.

Clearly, farmers contest vehemently any solution, which involves an overall decrease in regional income and strong disparities in impacts according to areas and production systems. By disaggregating the impacts, however, the model allows gains and losses to be quantified on the basis of both areas and systems. The introduction of compensation mechanisms could, therefore, be considered between areas and production systems, with the overall loss being a matter for public policy. Compensation mechanisms could be an area of further research, such as, for example, the mechanisms for the payment of public subsidies to the overall irreducible loss, and a market of rights between farmers, which could be ways of correcting inequalities between areas and systems.

The joint development of scenarios by stakeholders in an interactive user session of the model at the regional level is not a natural process. Indeed, it is more a question of seeking global solutions for all of the systems under external constraints. On the other hand, in a very similar project that has been carried out by the authors since, organising simulation game sessions, where each stakeholders manages a production system, allowed possible scenarios of changing developments to be highlighted based on the aggregation of strategic choices in the different production systems (Le Bars *et al.*, 2004). This step leads us to consider the global impact on the diversity of conceivable processes for the different production systems according to changing external constraints (technological developments, production choices, markets, regulations, *etc.*).

References

AGRESTE (2002) *L'agriculture en Tarn–et–Garonne*, Paris: Ministère de l'agriculture, de l'alimentation, de la pêche et des affaires rurales, Montauban: Direction départementale de l'agriculture et de la forêt.

Allaya, M., Attonaty, J.M., Le Bars, M., Le Grusse, P. and Mahjoubi, R. (2004) *MEDTER: Jeu de Simulation pour l'aide à la Décision en Agriculture*, CIHEAM-IAMM editions, ISBN: 2–85352–293–8, CD-ROM, p.157.

Antle, J.M. and Stoorvogel, J. (2001) 'Integrating site-specific biophysical and economic models to assess trade-offs in sustainable land use and soil quality', *Economic Policy and Sustainable Land Use*, pp.169–184.

AQUALIS, ARTLINE and OREADE (1997a) 'Etudes préalables au contrat de rivière Aveyron aval – Lère', *Rapport de phase I: diagnostic; qualité et gestion des ressources en eau*, Montauban: Conseil Général du Tarn et Garonne.

AQUALIS, ARTLINE and OREADE (1997b) 'Etudes préalables au contrat de rivière Aveyron aval – Lère', *Rapport de Synthèse du Rapport Définitif*, Montauban: Conseil Général du Tarn et Garonne.

Attonaty, J.M. and Le Grusse, P. (1994) 'Helping farmers in strategic decision-making. Training of executives from different Mediterranean countries: an experiment', in B. Jacobsen, D. Pedersen, J. Christensen and S. Rasmussen (Eds.) *Farmers' Decision Making, A Descriptive Approach*, Copenhagen: Institute of Agricultural Economics, 38th EAAE Semi-ton, 3–5 October, pp.235–245.

Attonaty, J.M. and Soler, L.G. (1992) 'Aide à la décision et gestion stratégique: un modèle pour l'entreprise agricole', *Revue Française de Gestion*, No. 8, pp.45–54.

Attonaty, J.M., Chatelin, M.H. and Garcia, F. (1999) 'Interactive simulation modelling in farm decision-making', *Computers and Electronics in Agriculture*, Vol. 22, pp.157–170.

Barbier, B. and Bergeron, G. (1999) 'Impact of policy interventions on land management in Honduras: results of a bioeconomic model', *Agricultural Systems*, Vol. 60, pp.1–16.

Batut, S. (2001) *Confrontation des points de vue des acteurs locaux sur la gestion de l'eau dans le bassin versant de l'Aveyron aval Lère*, Mémoire fin d'études pour le DAA Agro-Environnement, Université Montpellier I, ENSAM.

Bel, F., Lacroix, A., Mollard, A. and Regaraiz, E. (1999) 'Réduire la pollution azotée: les choix préalables d'une politique publique', *Courrier de l'environnement de l'INRA*, Mars, No. 36, pp.7–24.

Belhouchette, H. (2004) *Evaluation de la durabilité de successions culturales à l'échelle d'un périmètre irrigué en Tunisie: utilisation conjointe d'un modèle de culture (CropSyst), d'un SIG et d'un modèle bio-économique*, Thèse de doctorat en Sciences Agronomiques, Ecole Nationale Supérieure d'Agronomie de Montpellier, UMR Fonctionnement et conduite des systèmes de culture tropicaux et méditerranéens.

Benslimane, O. (1999) 'Pollution des eaux par les nitrates: détermination d'un cahier des charges agri-environnementales et analyse de son impact économique-écologique. Application au bassin versant d'Auradé (Gers, France)', *Thesis Master of Science*, CIHEAM-IAMM, Montpellier, p.134.

Carmona, G. (2004) 'Modèles de simulation de l'agriculture d'un bassin versant. Application au bassin Aveyron aval – Lère', *Master Professionnel Gestion des Exploitations Agricoles et Environnement*, CIHEAM-IAM, Montpellier.

Cretenet, M. (1995) 'Conception de systèmes de culture durables. Expérimentation et enquête dans l'étude de la fertilité des sols', in CIRAD (Ed.) *Sustainable Land Management in African Semi-Arid and Subhumid Regions, Proceedings of the SCOPE Workshop*, Dakar, Senegal, Montpellier-France, 15–19 November 1993, pp.131–139.

Falconer, K. and Hodge, I. (2001) 'Pesticide taxation and multi-objective policy-making: farm modelling to evaluate profit/environment trade-offs', *Ecological Economics*, Vol. 36, pp.263–279.

Flichman, G. (1997) 'Bio-economic models integrating agronomic, environmental and economic issues with agricultural use of water [on line]', in B. Dupuy (Ed.) *Aspects économiques de la gestion de l'eau dans le bassin méditerranéen: actes de l'atelier de Marrakech*, Bari (Italie): CIHEAM-IAM, Options Méditerranéennes: série A. Séminaires méditerranéens, 17–19 May 1995, No. 31, pp.327–336.

Flichman, G. and Jacquet, F. (2003) 'Le couplage des modèles agronomiques et économiques: intérêt pour l'analyse des politiques [en ligne]', *Cahiers d'Economie et Sociologie Rurales*, Communication présentée au Séminaire en économie de la production, 28–29 November, 2001 à Paris, Avril–Juin, No. 67, pp.51–69.

Foltz, J.C., Lee, J.G., Martin, M.A. and Preckel, P.V. (1995) 'Multiattribute assessment of alternative cropping systems', *American Journal of Agricultural Economics*, Vol. 77, pp.408–420.

Haggar, J., Ayala, A., Diaz, B. and Reyes, C.U. (2001) 'Participatory design of agroforestry systems: developing farmer participatory research methods in Mexico', *Development in Practice*, London: Intermediate Technology, Vol. 11, No. 4, pp.417–424.

INRA (1970) *Carte des sols dans la région de l'Avyeron Lère*, Chambre d'agriculture Midi-Pyrénées.

INRA (1989) *Carte des sols dans la région de l'Avyeron Lère*, Chambre d'agriculture Midi-Pyrénées.

Just, R.E. and Antle, J.M. (1990) 'Interactions between agricultural and environmental policies: a conceptual framework', *American Economic Review*, Vol. 80, pp.197–202.

Kuntashula, E. and Mafongoya, P.L. (2005) 'Farmer participatory evaluation of agroforestry trees in eastern Zambia', *Agricultural Systems*, Vol. 84, pp.39–53.

Le Bars, M., Allaya, M., Le Grusse, P. and Attonaty, J.M. (2005) *OLYMPE, Manuel d'utilisation*, CIHEAM-IAMM editions, ISBN: 2–85352–305–5, p.120.

Le Bars, M., Le Grusse, P., Allaya, M., Attonaty, J.M. and Mahjoubi, R. (2004) 'NECC: a simulation game to help collective decision-making', *WADEMED (Water Demand Management Knowledge Base in the Mediterranean*), Rabat, Maroc, 19–21 April.

Le Grusse, P. (2001) 'Du "Local" au "Global": Les dynamiques agro-alimentaires territoriales face au Marché Mondial. Quels instruments d'aide à la décision pour l'élaboration de Stratégies Territoriales?', *Options Méditerranéennes*.

Majhoubi, R. (2002) 'Analyse des systèmes de production agricoles et construction d'un modèle de simulation régional. Région du Contrat de rivière Aveyron Aval-Lère. Tarn et Garonne. Analyse typologique et zonage Simulation des percolations de nitrates avec un modèle agronomique', *DEA 'Economie du développement agricole, agro-alimentaire et rural'*, CIHEAM-IAMM.

Mendoza, G.A. and Prabhu, R. (2005) 'Combining participatory modeling and multi-criteria analysis for community-based forest management', *Forest Ecology and Management*, Vol. 207, pp.145–156.

Menon, D. (2000) 'Diversité et modélisation d'exploitations irriguées dans le bassin de la Lère', *ENESAD – Dijon. Série Irrigation R&E 2000-11*, September.

Mickwitz, P., Melanen, M., Rosenström, U. and Seppälä, Y. (2005) 'Regional eco-eciency indicators e a participatory approach', *Journal of Cleaner Production*, in press.

Okali, C., Sumberg, J. and Farrington, J. (1994) *Farmer Participatory Research: Rhetoric and Reality*.

Pacini, C.A., Wossink, G., Giesen, G., Vazzana, C. and Huirne, R. (2003) 'Evaluation of sustainability of organic, integrated and conventional farming systems: a farm and field-scale analysis', *Agriculture, Ecosystems and Environment*, Vol. 95, pp.273–288.

Rauschmayer, F. and Risse, N. (2005) 'A framework for the selection of participatory approaches for SEA', *Environmental Impact Assessment Review*, Vol. 25, pp.650–666.

Revel, J.C. (1982) 'Formation des sols sur marnes. Etude d'une chronoséquence et d'une toposéquence complexes dans le terrefort toulousain', *Thèse Sci., INP Toulouse*, p.249.

Siebenhüner, B. and Volker, B. (2005) 'The role of computer modelling in participatory integrated assessments', *Environmental Impact Assessment Review*, Vol. 25, pp.367–389.

Wu, J. and Babcock, B.A. (1999) 'Metamodelling potential nitrate water pollution in the Central United States', *Journal of Environmental Quality*, Vol. 28, No. 6, pp.1916–1928.

Notes

1 AQUAE: Action Scientifique Structurante AQUAE du CEMAGREF et de l'INRA : *Outils d'aide à la gestion concertée des ressources en eau.*, http://www.lisc.clermont.cemagref.fr/Labo/activite_recherche/projets/Projets_en_cours/ASSAQUAE/ASSAQUAE.htm.

2 Progress Report (2000) for l'Action Scientifique Structurante AQUAE (INRA-CEMAGREF-IAMM), http://www.lisc.clermont.cemagref.fr/Labo/activite_recherche/projets/Projets_en_cours/ASSAQUAE/ASSAQUAE.htm.

3 The software was developed at INRA-Grignon by J.M. Attonaty.