Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis

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Abstract

This paper presents a spatial multi-agent programming model, which has been developed for assessing policy options in the diffusion of innovations and resource use changes. Unlike conventional simulation tools used in agricultural economics, the model class described here applies a multi-agent/cellular automata (CA) approach by using heterogeneous farm-household models and capturing their social and spatial interactions explicitly. The individual choice of the farm-household among available production, consumption, investment and marketing alternatives is represented in recursive linear programming models. Adoption constraints are introduced in form of network-threshold values that reflect the cumulative effects of experience and observation of peers' experiences. The model's economic and hydrologic components are tightly connected into a spatial framework. The integration of economic and hydrologic processes facilitates the consideration of feedback effects in the use of water for irrigation. The simulation runs of the model are carried out with an empirical data set, which has been derived from various data sources on an agricultural region in Chile. Simulation results show that agent-based spatial modelling constitutes a powerful approach to better understanding processes of innovation and resource use change. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Simulation models are gaining importance as tools for managing tomorrow's agriculture, since they allow the study of a wide range of price and trade policy options. In agricultural economics, simulation models that predict the behaviour of individual decision-makers are typically based on mathematical programming methods. In these models, individual decision-making is usually aggregated at the regional or sector level in order to evaluate policy options. The advantage of such models is that they are robust and less demanding concerning the availability of aggregate data than econometric models. This makes them attractive, especially for policy analysis in transition and developing countries.

However, apart from the well-known problem of aggregation error and the tendency to overspecialisation, conventional simulation models based on mathematical programming suffer from two weaknesses. First, they do not explicitly capture the interaction between actors (i.e. the individual farm-households), which is equivalent to the assumption that there are no

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transaction and information costs. Second, these models do not fully take into account the spatial dimension of agricultural activities and, thus, neglect the role of internal transport costs and the physical immobility of land. Consequently, the explanatory power of these models is rather moderate for research questions that involve the diffusion of innovations or locally adapted resource use where interaction and space usually play a decisive role.

Against this background, the study presented here (Berger, 2000) attempted to develop a new mathematical programming approach for the prediction of diffusion processes, natural resource use changes and policy responses. The model's applicability is tested on an empirical policy-related research question in Chile. The research was funded by the Deutsche Forschungsgemeinschaft (DFG) and carried out in co-operation with the University of Talca and the Center for Technology Evaluation in Linares (Berger, 1997). The project draws on Balmann (1997), who pioneered the use of farm-based linear programming within a cellular automata (CA) framework.

2. Problem and objectives

Demand for a new type of model arose from the quest for adequate policies to improve the competitiveness of Chilean agriculture in the context of the Mercosur free-trade agreement.

In 1996, tariffs were cut by 30% on the average. It was also agreed to specify exceptions for some rather sensitive agricultural products such as wheat, flour and sugar. Tariffs on these products remained at the level of 1996, until the end of the agreed adjustment period, which will be around 2014. Accompanying the ratification of the treaty in 1996, several studies were commissioned that were aimed at reducing the fears of the rather traditional Chilean farmers. The overall result of these studies was that farmers will in fact suffer income losses, but only if they continue to produce import commodities. However, Chilean farmers do have a considerable comparative advantage over other Mercosur countries if they produce export commodities. Hence, the challenge for Chilean farmers is to invest in new technologies in order to take advantage of increasing prices for export goods. Given that irrigation is required for most export farm-

ing activities, resource use changes and water-saving innovations are a hot issue in agricultural extension. Political bargaining started on how to support the adjustment and modernisation process of Chilean agriculture. Despite the importance of innovation, there exist only a few and rather informal studies about the likely outcomes of market-driven technical and structural changes in Chilean agriculture.

The objective of this research was to develop a new multi-agent modelling approach which (1) reduces the weaknesses of mathematical programming mentioned above, and (2) provides insights into the diffusion of innovations and water resource use.

The simulation tool should help to clarify the following questions:

- What will be the likely patterns of diffusion for specific innovations?
- Can we expect substantial changes in the use of water as a result of water-saving irrigation methods?
- Will these innovations create sufficient incomes and also reach traditional farmers?
- What will be the structural effects of a 'treadmill' innovation process, to use Cochrane's (1979) terminology?

3. Underlying model philosophy

In Section 3.2, I outline some methodological thoughts on model building, which favour the application of a spatial farm-based programming approach to the adoption of innovations and resource use changes. Since the concepts of multi-agent systems (MAS) and CA are borrowed from the computer sciences, a short explanation may be helpful. For an overview on these and other artificial life techniques applied to social science simulations, refer to Gilbert and Troitzsch (1999).

MAS are computer systems composed of autonomous entities or agents which have only limited knowledge and information processing capacities. While agents can be as simple as subroutines of a computer program, typically they are larger entities with some sort of persistent control. Good examples are personal electronic assistants that search for information on the internet, arrange their owners' time schedules and assist car drivers. Accordingly, on a

more abstract level, their purpose is to solve larger and complex problems that one centralised unit cannot tackle, because too much information and computation power would be required. In MAS, agents interact and exchange information in a decentralised and somewhat 'social' manner instead, which explains why the term 'Distributed Artificial Intelligence' was coined. Particularly, this last aspect makes MAS an interesting tool for social sciences. The idea is to use computer simulations with human like agents in order to study how an aggregation of individuals leads to complex macro behaviour. These in silicio experiments will help to test the hypotheses on the fundamental social mechanisms in human societies. CA can be used to model the agents' interactions in the physical or social space. Typically, the agents occupy positions on a two-dimensional grid of cells and the distances between them influence their interactions.

An extensive literature has emerged both on the methodology and the use of mathematical programming models in predicting supply response in agriculture. Hanf (1989) provides an assessment of the two extreme prototypes of agricultural sector models, which may be very briefly summarised as follows. The 'simultaneous equilibrium approach' generally assumes a perfect co-ordination mechanism and maximises a common sectoral utility function. In contrast, the 'representative independent farm approach' consists of a number of farm models which are independently calculated and then added up to a sector result. The second approach seems to be a preferred model choice, if sector development is characterised by (1) imperfect markets, (2) different behaviour than pure profit maximisation and (3) adjustment processes. The same arguments apply in principle to the multi-agent programming approach. As will be shown in the remainder of this section, the multi-agent concept additionally facilitates the consideration of inter-household linkages and of space.

3.1. Arguments for using a multi-agent programming approach

1. A farm-based programming approach allows for a pragmatic treatment of data availability in transition and developing countries where consistent aggregate data hardly exist. Information from various sources such as agronomic results from experimen-

tal stations, official and unpublished farm records and sample surveys, experts' opinions and direct observations on field trips can be incorporated.

2. Policy makers and institutions pursuing technology transfer have a great interest in predicting the diffusion of specific innovations and in assessing the policy implications for 'typical' farm-households. Both technical and financial constraints on the farm level can easily be introduced into a farm-based programming approach.

3. The set of activities which are technically and financially feasible for a farmer is influenced by behavioural constraints that reflect the cumulative effects of experience and observations of his neighbours' experiences. Therefore, one should consider some form of heterogeneity of behaviour in order to capture time lags in farmers' choices among alternative technologies. For the programming approach, this implies that several single farm models with different behavioural constraints have to be solved simultaneously, which is possible in a MAS.

4. A multi-agent model is able to capture the most important interactions between farm-households. One type of interaction is the exchange of information about new technologies that is essential for the individual innovation decision. As findings from the innovation diffusion literature show, a 'critical mass' of convinced users must be reached before an innovation will spread. The finest approach to modelling this phenomenon might be to internalise the communication process between the individual programming models, because otherwise one would have to establish the time of adoption more or less 'ad hoc' for each model and each policy scenario. Herein, lies the real merit of MAS, since it facilitates the solving of autonomous programming problems while exchanging variables between them.

5. Similar considerations as in step 4 apply to another type of interaction: the exchange of locally available resources such as water and land. These factors of production are usually subsumed under the notion of 'non-tradable' goods. Because of their importance for agriculture, the incorporation of land and water markets in MAS with an endogenous price formation represents a notable improvement over conventional models.

6. Different kinds of analysis can be undertaken in a dynamic model setting. The main research interest of the project presented here is to analyse the path of agricultural development without imposing the final outcome, as it is done in the comparative-static models used in many studies. The idea behind this approach is to define constituent parts of an agricultural region and to establish some rules concerning their dynamics. Having set up a starting situation, the model is run and a kind of self-organising process can be observed at the aggregate regional level. By variation of particular model variables, e.g. prices or interest rates, one can explore the structural evolution that might unfold in response to changing policy conditions. Thus, the approach can be best described as conducting experiments in an artificial world in order to obtain insights for policy development and evaluation.

3.2. Arguments for using a spatial cellular automata model

The next question to be raised in this context is why the spatial dimension of agricultural activities should be considered in farm models.

1. From the farm management theory, it is well-known that internal transport costs limit farm growth. Farms mainly compete with their neighbours for land and, therefore, depend on the local supply of and demand for land. In rural areas, where many farms with a high marginal productivity attempt to expand their acreage, this can lead to excessive land prices that may even prevent the realisation of economies of scale. Ignoring these spatial dynamics by assuming perfect land allocation among farms is not always an adequate representation of reality.
2. The particular role of spatial relations in the use of water for irrigation also requires a spatial model. Technologies with low irrigation efficiencies used by upstream farmers generate high return flows that can be reused by downstream farmers. Accordingly, the spatial distribution of freshwater utilisation and reuse is essential for farm models in developing countries where irrigation efficiency is typically low.

3. Soils of different cultivation qualities and water supply determine the spatial variation of particular land use systems to a certain extent. Newly available technologies and policy interventions may alter this distribution, especially in the case of irrigated farmland. The same applies to organisational innovations such as jointly used infrastructure or cultivation practices with a high degree of spatial co-ordination, e.g. as integrated pest management. Spatial models are required to capture these issues.

4. Model implementation

The newly designed MAS–CA model consists of two main components: an economic sub-model and a hydrologic sub-model, which are tightly connected to a consistent spatial framework (Fig. 1). This section provides a short model description with emphasis on the technology adoption process. For a listing of model parameters and equations consult Berger (2000).

4.1. Farm-based mathematical programming

As far as the economic sub-model is concerned, a recursive linear programming approach is implemented but with a decisive novelty. Each farm-household in the study area is captured in the model and solves its decision problems over time autonomously. Several types of interactions between farms are considered: contagion of information, exchange of land and water resources and return-flows of irrigation water. Correspondingly, one might call this a highly disaggregated farm programming approach with inter-household linkages. The farm-households are assumed to seek to maximise expected family incomes without exhausting their land and water assets. Adoption of innovations is conceptualised as a farm investment problem under uncertainty. The agents' complex decision-making processes are decomposed into sequences of smaller linear programming problems that are solved separately for each agent (Fig. 2). Following Day and Signo (1978), there is "sub-optimising with feedback", i.e. the agents attempt to maximise their expected income in a sequential, local optimisation procedure that takes into account the agents' previous experiences. In the case where the returns to family-owned resources fall below certain thresholds,
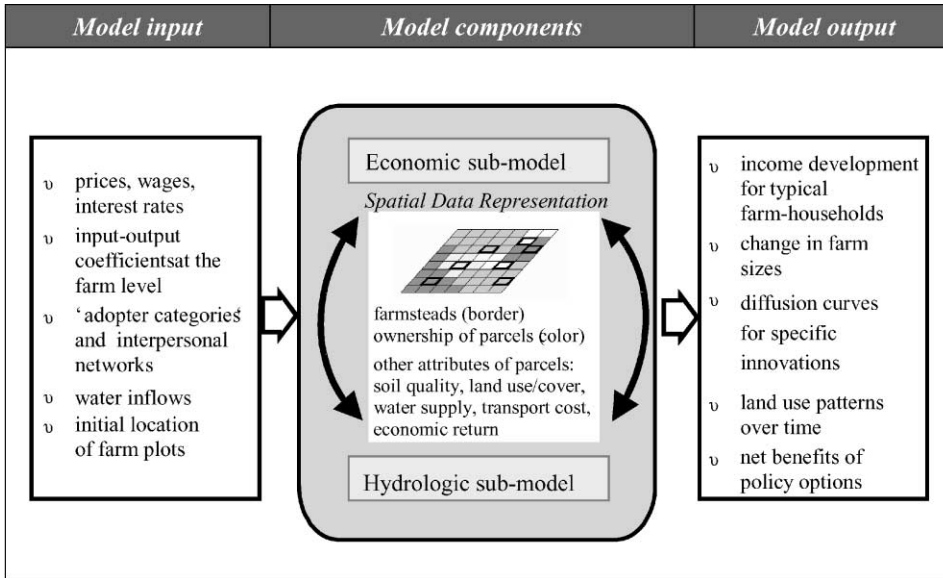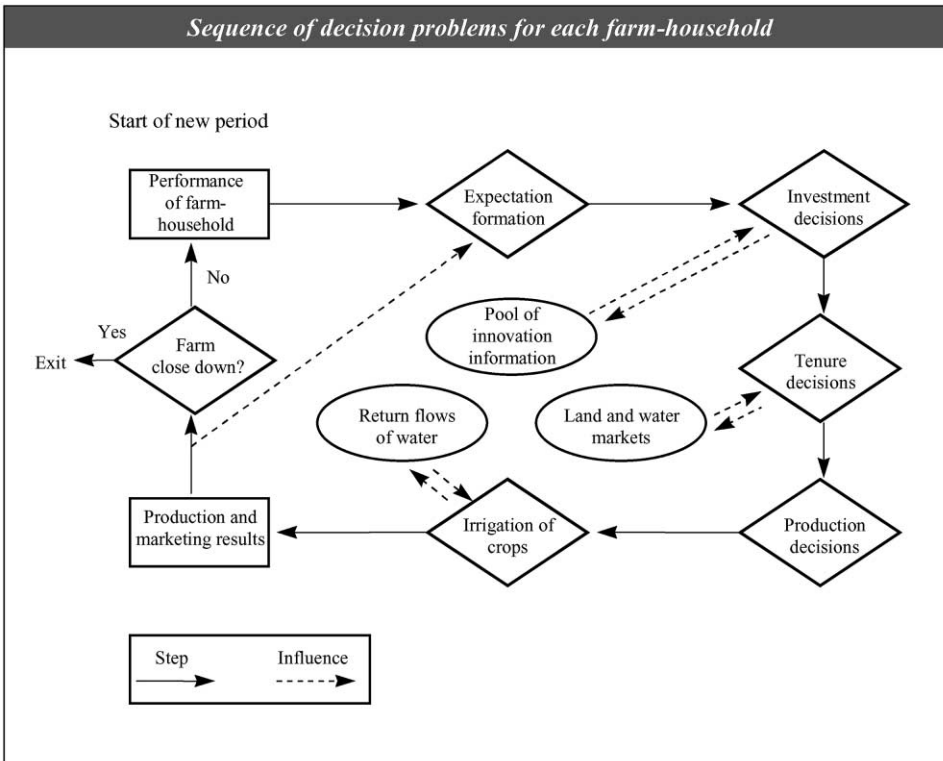
Fig. 1. Model components.

Fig. 2. Flowchart of the simulation model.

the models' farm-agents are willing to give up agricultural production and leave the farm business.

4.2. Technical change

The innovation economics literature, as cited in Dosi et al. (1988), regards modern farm production as a typical example of a supplier-dominated sector. Technical improvements are largely incorporated in process innovations such tractors, fertilisers and pesticides, which are generated in the input supplying industry. The focus of this model approach is therefore, placed on the adoption of agricultural innovations by farms. Specific supply factors of technical change are neglected. This simplification can also be justified by the commonly accepted hypothesis that demand factors are largely responsible for the speed of diffusion in agriculture (Griliches, 1957). Technologies that appear to be promising in the near future become available to the farm-households in the simulation runs and diffuse through the farm sector. Obviously, two extreme scenarios define the 'possibility space' for future technology diffusion in the farm sector. On one hand, farmers might adjust 'smoothly' to exogenous technical changes as predicted in the standard economic approaches. On the other hand, one might assume conservative farmers who are reluctant to innovate and refuse any technology adoption. Reality will probably lie somewhere between these two boundaries. The model presented here helps to explore the economic potential of new technologies along alternative development paths.

4.3. Heterogeneity of behaviour

In decision-theoretic terms, two variables affect the behavioural heterogeneity of farmers during the diffusion process of a specific innovation. First, the net benefits from adoption which traditional farm investment analysis can 'objectively' measure. Second, all other costs that relate to the farmer's managerial capacity and are usually referred to as adoption costs. These include information and planning costs, socio-psychological adjustment costs, temporary production losses as well as 'subjective' risk premiums and option values. Metcalfe (1988, p. 564) provides a good illustration of how the diffusion process in the farm sector emerges from the frequency distribution

of these two variables. Following his concept, one can classify the farm-households into three groups with regard to their timing of technology adoption: "non-adopters" whose net benefits from adoption of a specific innovation are negative (presumably due to indivisibility or insufficient farm sizes), "potential adopters" who at present face prohibitively high adoption costs and "actual adopters" with positive net benefits after adoptions costs. Diffusion of the innovation occurs when relative price changes or technical improvements modify the distribution of net benefits and/or adoption costs and hence, more 'potential' adopters become 'actual'. As Metcalfe (1988) notes, the recognition of 'information contagion' or 'bandwagon effects' distinguishes the following two diffusion models. Equilibrium approaches assume that information sets are given and exogenous, while disequilibrium approaches acknowledge an endogenous chain-reaction type of 'contagion process'. A prominent example of the second approach is Cochrane's (1979) treadmill model in agriculture, which is based on different adoption costs. Farmers with a high management capacity and low individual adoption costs tend to adopt a new technology first; imitators follow when their initially higher adoption costs decrease due to information spillover. Much empirical evidence, as cited by Rogers (1995), supports this concept. At the most critical stages in their adoption decision process, farmers apparently rely on information brought to them by the peers.

4.4. Thresholds to adoption

If all farmers eventually adopt an innovation, the outcome of the contagion process over time usually approaches an S-shaped diffusion path. Typically the normal bell-shaped and the cumulative curve are partitioned into five adopter categories using the average time of adoption and the standard deviation (Table 1). Along the time path, the farmers behave as if they had thresholds to adoption. For example, the first farmers of the 'early adopter' segment adopt after the 'innovators' segment, which counts for 2.5% of the farm population has. The 'early majority' follows after the innovation has reached $2.5 + 13.5\%$ of the farmers, and so forth. Accordingly, one can interpret these cumulative percentages as 'adoption thresholds' for the farmers of the subsequent adopter category. If

Table 1
Adopter categories and thresholds[a]

	Innovators	Early adopters	Early majority	Late majority	Laggards
Frequency (%)	2.5	13.5	34.0	34.0	16.0
Cumulative frequency (%)	0.0	2.5	16.0	50.0	84.0

[a] Source based on Rogers (1995, p. 262)

one additionally assumes that relative prices remain constant and no post-innovative technological improvements occur, the following decision rule at the farm level leads to the same time path.

- *Step* 1: Monitor the present adoption level and compare it with the individual threshold.
- *Step* 2: If the threshold is reached, calculate the farm's net benefits from the adoption.
- *Step* 3: If the net benefits are positive, adopt the technology.

Introducing a few more assumptions to this frequency-dependent diffusion model make it possible to predict the time path of the adoption of several production technologies simultaneously. The most important of the assumptions listed in Berger (2000) are: no change of thresholds over time; innovations do not differ in their 'primary' attributes (cf. Downs and Mohr, 1976); the existence of a 'natural' time intervals such as (Table 1) planting seasons when adoption decisions can only be made. As further extensions to this approach, one can (1) consider separate communication networks without information spillover by monitoring only the farmers belonging to the same network and (2) attribute higher weights to external information sources by lowering the above mentioned thresholds.

4.5. Empirical estimation of diffusion parameters

Net benefits of different production technologies can be derived from experimental data and easily introduced into the whole farm programming models. In contrast, the estimation of adoption costs and their changes over time usually poses problems due to poor data availability. Fortunately, network-thresholds have in principal the advantage of a better empirical measurability. As Valente (1995) demonstrates, individual network-thresholds can be straightforwardly computed from the network survey data. Since adoption thresholds contain the same information about

the underlying contagion process as adoption costs, the threshold approach is chosen for the research presented here. However, a complete network survey was not yet available for the Chilean study region and the network-thresholds had to be derived from the data provided by the extension service, an own project survey and in-depth interviews. Based on the intensive empirical work of Stallmeister (1995) and Sauer (1995), two distinct communication networks without information spillover were considered. On one hand, the *campesino* farms network consists of small-scale family holdings between 2.5 and 12.0 ha. On the other hand, the so-called 'commercial' farms network with farm sizes of more than 12.0 ha. Certainly, this network analysis is rather subjective and a follow-up study will have to conducted to provide more objective empirical network-thresholds.

4.6. Other empirical data

The simulations are carried out with an empirical data set that has been derived from various data sources on an agricultural region in Chile. The empirical investigation captured both the main agronomic and socio-economic features of the relevant region. The spatially disaggregated data set includes land of different cultivation qualities and water as an additional factor of production. A special module was designed to process and store the regional and individual farm data in a spatial database. In order to consider price changes due to the Mercosur agreement, price indices were computed based on Muchnik et al. (1996). In the alternative scenarios without the association to the Mercosur, input and output prices are fixed to their 1996 levels. Table 2 gives a summary of all the model variables and parameters.

4.7. Spatial dimension

As in most geographic information systems (GIS), the data are spatially organised in a grid of landscape

Table 2
Summary of model variables and parameters

Exogenously determined variables	Endogenous variables	Parameters
Market prices for 'tradables'	Prices for 'non-tradables'	Input–output coefficients
Interest rates	Acreages of crops	Depreciation rates
Wages	Yields	Sunk costs for fixed assets
Taxes and contributions	Investment levels	Unit transport cost
Minimum consumption level	Working capital expenditures	Network thresholds
Supply of land	Borrowing and saving levels	Expectation coefficients
Supply of freshwater	Labour utilisation	
Supply of innovations	Return-flows in irrigation	
Initial location of farms	Allocation of land and water	

units. Each cell or pixel has several biophysical and economic attributes associated with it: soil quality, water supply, land cover/land use, ownership, internal transport costs, marginal productivity or return to land. While the first attribute, 'soil quality' here is assumed to be constant, all the other attributes are influenced by the autonomous decisions made over the time by the model agents, i.e. the farm-households and non-farm owners. For example, water supply depends on the amount of individual water user rights traded on markets. Land cover/land use is derived from the farm's linear programming problem, taking into account the price expectations and technical and financial constraints. As far as ownership or tenureship is concerned, the model captures their changes when farmland is sold or rented. As a result, internal transport costs may also vary because of a cell's location and respective distance to the new farmstead.

4.8. Markets for land and water rights

As empirical findings show, land and water are hardly ever sold in Chile, but rental markets may play an important role in the local exchange of both the resources. To capture these features, rental markets for land and water are considered endogenously in the model. An auction module was designed to model bilateral trade between the agents. Farm-agents attempt to rent out land and water when their shadow prices for a particular parcel are below sector average. Since the internal transport costs between parcel and farmsteads are considered, it is mainly the neighbouring farm-agents that compete for the offered land. The temporary land use right is then transferred

to the neighbour with the highest shadow price for the specific parcel. For the purpose of simplicity, strategic behaviour is not taken into account and the individual level of rent is fixed at the average of the corresponding offer and request.

4.9. Return-flows of irrigation

The water resources sub-model is subdivided into sections in order to capture the locally available freshwater supplies and return-flows. Equations and parameters are derived from a water engineering study for the Chilean Department of Public Works. The sub-model establishes a monthly water balance for each section, starting with the upstream sections. The farms receive their individual freshwater and return-flows quota according to their water user rights. They irrigate their farmlands, thereby producing return-flows to users downstream. The farms apply certain decision rules as far as the temporary or permanent abandonment of crops is concerned. The threshold linear relationships are assumed with respect to the crop–water production function.

4.10. Simulation experiments

The research region covers an area of roughly 667 km² and is represented in the model with a resolution of about 158 m × 158 m. Hence, the size of grid cell is 2.5 ha. Since each grid cell corresponds to a farm parcel, farm sizes are measured to the nearest 2.5 ha. The spatial model is sub-divided in 20 sections in order to consider the return-flows from upstream to downstream farmers. Each of the 5400

farm-households (90% *campesino*) regarded in the model solves its investment, annual production and tenure decisions problems by the use of mixed-integer programming (dimension of the LP matrix: 120×240, around 1.4 million problems solved per simulation run). Based on the exhaustive field trials by the Center for Technology Evaluation, 32 innovative crops and water-saving techniques were chosen to be included in the model and diffused during the simulation runs. The farm-agents select among these innovations and adopt according to their relative profitability. In the bandwagon scenarios, however, farm-agents only have access to those innovations which have reached their network-threshold. The technological possibilities of the *campesino* and commercial holding types differ for some farming activities due to indivisibilities. Heavy machinery, certain export fruit plantations and irrigation methods are only available to the large-scale commercial farms. Apart from the pure market-driven scenarios with and without Mercosur, policies on credit and subsidies to farm production are analysed.

4.11. Software

This newly designed MAS–CA model has MS-Windows 32 bit and UNIX portability. Input and output files are in ASCII-text format and can be processed with common spreadsheet and graphics programs. The source code is written in C++ object-oriented programming language and permits modular extensions to include, e.g. ecological constraints or to create interfaces with GIS-applications.

5. Model calibration and robustness

The calibration of a MAS–CA model is rather challenging since the model has to approximate real-world observations on the micro level (farm-households) as well as on the macro level (research region). In this study, a two-step approach is followed: first, validation experiments on the micro level, where typical model agents are compared to real-world farm data; and second, macro level experiments in order to test the model's aggregate representation. The calibration procedure is repeated until a sufficient model fit at both

levels is achieved. Unfortunately, only the real-world observations on land use distribution in 1996 were available for the micro level. Therefore, the model's ability to replicate reality can only be checked for the initial simulation period. Land use results from the model were regressed on their observed values to generate a simple goodness-of-fit — perfect association would be indicated by an intercept of 0 and a slope of 1. On the micro level, the regression yields a slope of 0.977 (S.E. = 0.01, $R^2 = 0.991$) and on the macro level of 0.704 (S.E. = 0.107, $R^2 = 0.657$). The model probably overestimates the cultivation of maize and some legumes, and underestimates wheat cultivation. Given that gross margins for these crops are fairly comparable and their regional values are only rough estimates, the model fit seems sufficient for this study. Needless to say, the standard errors are only informal criteria since the model results are not strictly independent. Change or tracking experiments as suggested by McCarl and Apland (1986) remain to be done in a follow-up study, which will collect more field data. However, local experts considered the model's predictive capacity to be plausible.

In addition, robustness tests are of extreme importance for simulation models that contain many degrees of freedom and with highly recursive dynamics. Especially in this study, where empirical data were combined with rather informal observations and random-generated synthetic data, the model should produce non-erratic results within a broader range of parameter variations. Therefore, the model's robustness was tested by using two variables, average income and on-farm labour allocation in different adopter categories, which directly reflect changes in the farm organisation. With identical starting conditions, these indicators show very little variation in repeated simulation runs (<1%, except for the innovators' group income where about 6% variation was found due to the small size of this group). In the case of changing starting conditions, variation was obviously higher when the initial endowment with fruit plantations was altered by more than 100%. Fruit production requires considerable labour input and generates high incomes. Though absolute values of both indicators differ in these special scenarios, the relative trends are uniform. As a consequence, the model seems robust enough to compare different scenarios under identical starting conditions.

More details on the robustness experiments and supportive statistical tests can be found in Berger (2000).

6. Technological and policy scenarios

The MAS–CA model provides the opportunity to carry out a wide range of technological and policy scenarios by variation of the following parameters:

- *Input and product prices*. Different exogenous price regimes make it possible to simulate scenarios with and without the association to Mercosur.
- *Credit market conditions*. Chilean extension clients enjoyed preferential access to credit in the form of subsidised loan rates and lower minimum shares of equity capital. The model facilitates implementation of such client-specific policies as well as special government investment programs for large- or small-scale farm enterprises.
- *Cash expenditures*. By variation of farm and non-farm cash expenditures, either coupled or uncoupled to land, government interventions such as direct income transfers, personal taxes and land taxes can be taken into account.
- *Labour opportunity costs*. Consideration of specific labour opportunity costs provides insights into rural–urban migration and generation cycles. It can be assumed that households quit the farm business when they reach certain thresholds for off-farm wages. Also younger farmers often have better off-farm job opportunities and, as a result, farms may close down when the older generation retires.
- *Water supply*. Variations of fresh water supplies and distribution losses make it possible to analyse very dry years as well as investments in improved irrigation infrastructure.
- *Land and water markets*. Dynamics on rental markets can be driven by activity coefficients for special scenarios. Differences in shadow prices for a specific plot may not attain certain thresholds, thus, preventing the transaction between potential tenants and landowners.
- *Price and water supply expectations*. It is possible to consider different forms of expectations, e.g. static, adaptive and perfect foresight, in order to analyse the role of behavioural heterogeneity in the process of innovation and farm adjustment.

- *Adoption costs and network-thresholds*. These parameters are used to predict the diffusion of specific innovations under different assumptions concerning communications between farm-households. Scenarios with complete a priori information (zero adoption costs — ideal technical change), frequency-dependent contagion processes (bandwagon effect) or excess inertia (prohibitively high adoption costs — without technical change) can be simulated.

Policy options, which have direct effects on model variables such as prices or credit schemes, can be readily tested for their repercussions on the supply response and farm incomes. It is by far more challenging to assess the impacts of indirect effects such as agricultural extension programs. One possibility is to run the model with ad hoc assumptions about the effectiveness of extension on adoption thresholds and then examine the model's sensitivity.

7. Selected simulation results

In this section, some simulation results will be discussed to demonstrate the model's applicability to policy-related research questions. As indicated above, resistance of the farm sector and especially the Chilean farmers association to Mercosur is rather fierce. With a view to this disagreement, several policy options are being discussed in Chile and attempts are being made to modernise national agriculture by promoting the diffusion of innovations. The agent-based simulation model attempts to answer the questions listed in Section 2 and helps to identify winners and losers among the farm holdings.

First, the simulation runs reveal several typical diffusion patterns as shown in Fig. 3. Certain innovations such as 'contract farming' diffuse rapidly and reach very high saturation levels among the commercial farm holdings. Behavioural heterogeneity and communication effects do not play a key role as compared to the example 'horticulture' in the case of *campesino* farms. Here, we find remarkable differences in diffusion speed and saturation level if less ideal technological conditions are assumed. Such patterns might justify some form of government intervention in order to 'speed up' the diffusion bandwagon. A third
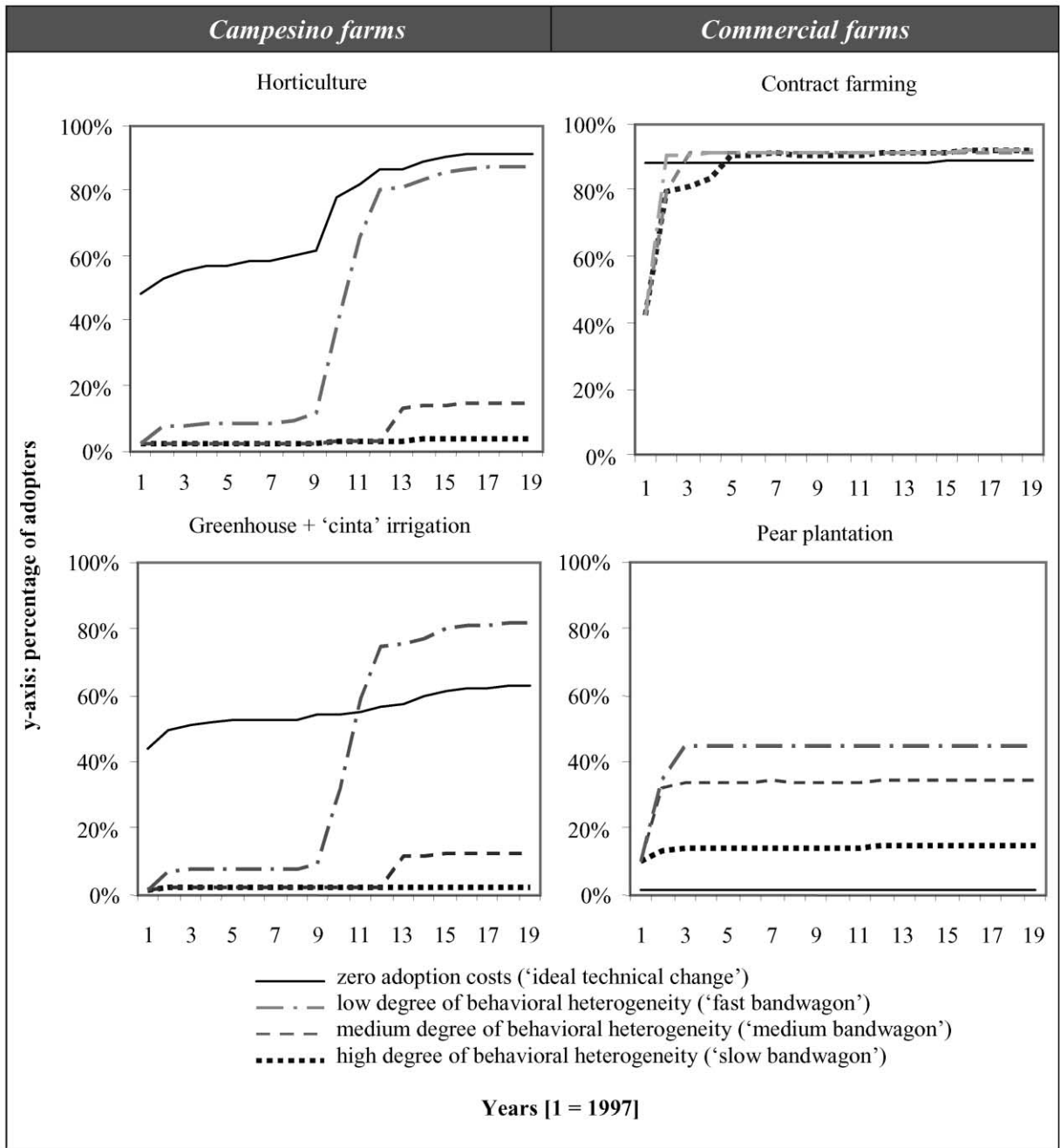
Fig. 3. Selected diffusion patterns in Mercosur scenarios (share of adopters in %).

pattern illustrates the potentially path-dependent nature of diffusion processes as described by Cowan and Gunby (1996). If a low degree of behavioural heterogeneity is assumed, the innovation 'pear plantation' diffuses quickly and reaches almost 40% of the commercial farms. Once the bandwagon is moving, more farmers are persuaded to adopt than would be the case with complete a priori information. Under ideal technological conditions, other innovations appear more profitable and no significant diffusion of 'pear plantation' occurs. The fourth pattern for 'greenhouses with Chilean cinta-irrigation' underlines the relevance of the multi-technological competition and selection process proposed by Metcalfe (1988). Ideal technical change would imply an initially high level of adoption, whereas, under behavioural heterogeneity diffusion is delayed for several years. Then the bandwagon speeds up and leads to an even higher level of saturation. Apparently, the relative advantage of this innovation changes among *campesino* farms when fewer competing innovations, as compared to the ideal technological scenario, are available for the less innovative farmers. Consequently, the usual dichotomy found in diffusion studies, old versus new technology, might capture only a small fragment of the complete picture and suggest misleading recommendations for technology transfer programs.

A similar argument applies to the public efforts to promote the adoption of modern water-saving irrigation techniques as indicated by Fig. 4. The potential for water-saving technologies in both holding types is high — ideal technical change would allocate about half of the total irrigated area to water-saving techniques within only 10 years. However, this seems rather optimistic, at least if we trust the model results for the two bandwagon scenarios in which only one-fifth of the total irrigated area is used for modern techniques such as drip, sprinkler or improved furrow irrigation.

It is often stated that change agencies and policy makers are best advised to increase their focus on how the farmers perceive technological alternatives and which income these innovations are able to generate. As Fig. 5 confirms, association with Mercosur offers a notable income potential for Chilean agriculture, at least in the research region with its relatively favourable agro-ecological conditions. However, this income potential will only be exploited under the assumption of a very optimistic ideal innovation process. If behavioural heterogeneity and bandwagon effects are introduced, the model income results appear almost as modest as under the fully pessimistic scenario without technical change. Massive government support, which was demanded by the Chilean farmers association in 1996, may help to increase the
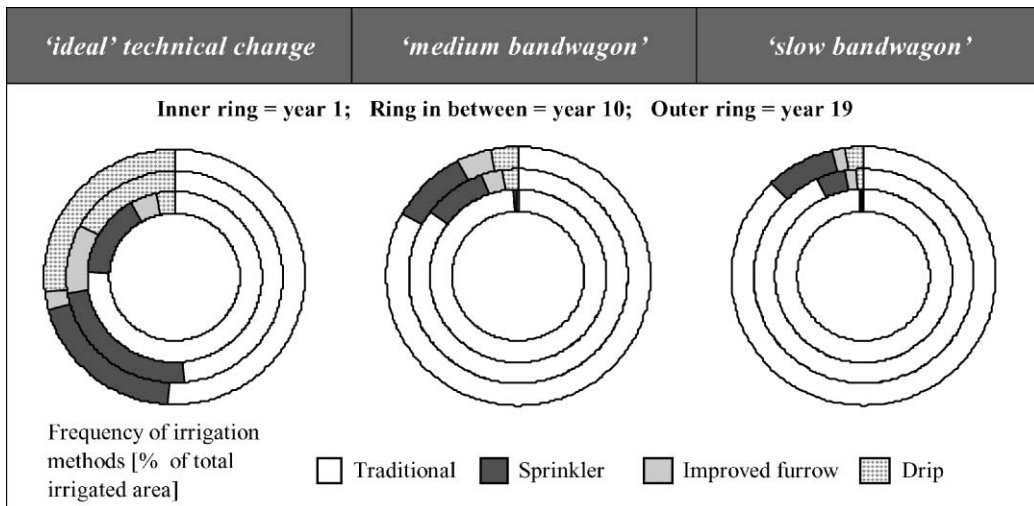

Fig. 4. Diffusion of water-saving irrigation methods in both the networks together in Mercosur scenarios (percentage of total area dedicated to different methods).
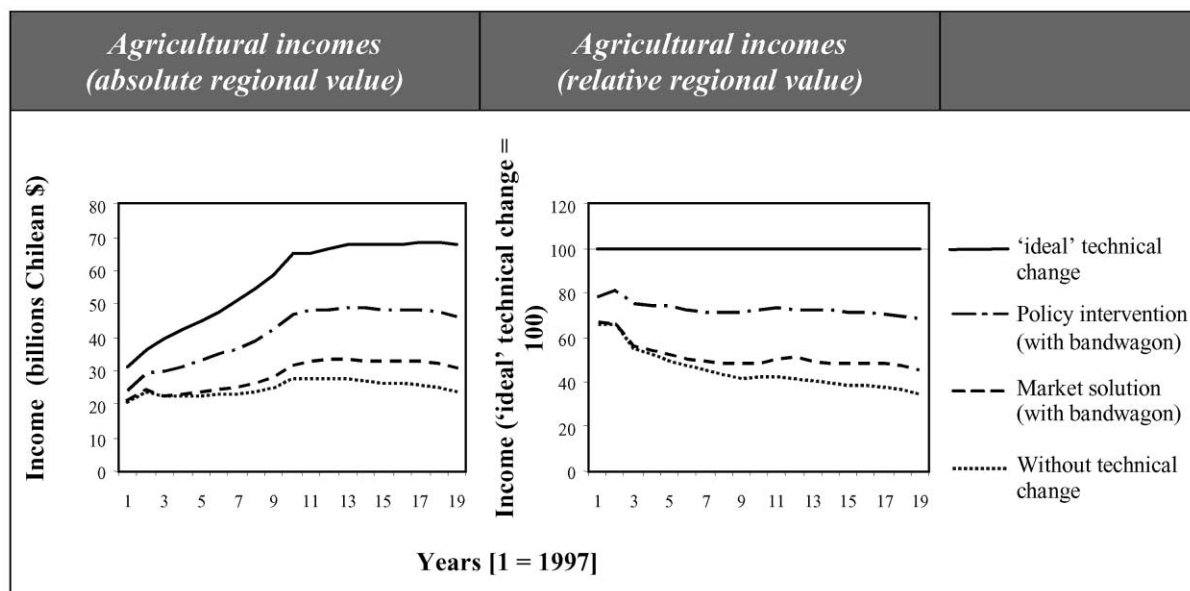
Fig. 5. Aggregate regional income of farm-households in Mercosur scenarios (billion Chilean $).

agricultural incomes. Then, of course, the question is whether the social net benefit is positive. More details on the income and policy analysis can be found in Berger (2000). For instance, average household incomes in the early and late adopter groups will apparently grow apart and then stabilise.

Cochrane (1979) argued that technical change in agriculture is a cannibalistic process in which the early bird farmers absorb the land resources of laggard farmers who have been driven out of business. The simulation runs also display a kind of 'treadmill' effect, though in this case the less innovative households voluntarily close down their farm enterprises. Fig. 6 shows the annual rate of change in the number of commercial and *campesino* farms over a 20 year horizon. While under 'ideal' technical conditions, the average annual rate is about 0.1%, the assumption of a bandwagon communication process leads to a considerable structural change. Especially in the case of commercial farms, almost 6% of the 'laggard' adopter segment disappears each year. Insolvency is not the main cause of closing down. Instead, increasing opportunity costs for land motivate households to give up agricultural production. However, since empirical data were not available on how farm-households respond to the

rising opportunity costs, model parameters are still based on ad hoc assumptions. A follow-up study will aim at clarifying these simulation results.

Other results, provided by the simulation experiments, relate to the so-called 'Schumpeter hypotheses' of industrial dynamics. According to these hypotheses, large-scale enterprises are more innovative and, therefore, grow faster than their small-scale competitors. Empirical counterexamples are often cited in the literature and the simulation runs suggest a less clear-cut relationship between farm size and farm growth as well. Fig. 7 depicts the change of farm size classes under 'ideal' and 'bandwagon' conditions. The initial number of farms in each class is normalised to 100 and compared with values in the years 10 and 19. Apparently, the underlying structural change in the bandwagon scenario leads to a decline in number of the small-scale farms and rather dynamic increases in the middle farm size classes. Large-scale farms show less tendency to growth when acreage is used as a measure of farm size.

As far as the evolution of land and water rental prices is concerned, the model seems to replicate the real-world prices and quantities of 1996 quite well. For the subsequent years, the model predicts a slight
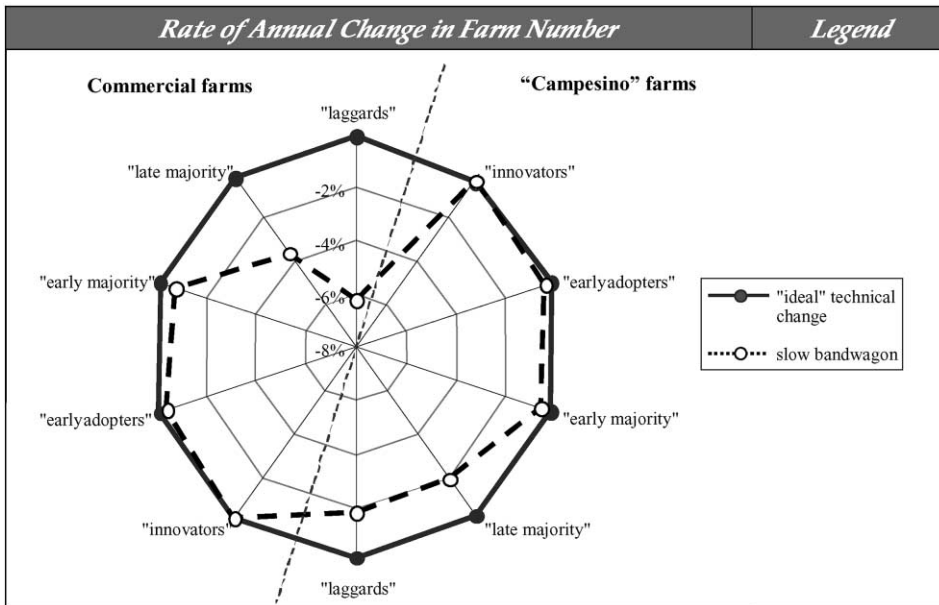
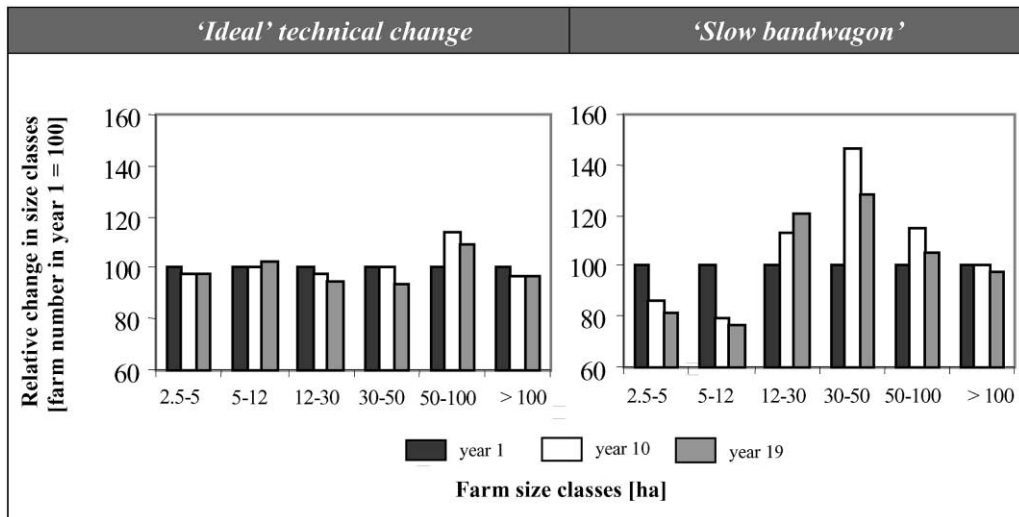Fig. 6. Average farm exits in Mercosur scenarios (% per year).

Fig. 7. Relative change in farm size classes in Mercosur scenarios (year 1 = 100).

upward tendency for land and water shadow prices. However, differences between agro-ecologically favoured and marginal locations are apparent. The rising number of parcels offered for rent in the bandwagon scenarios mitigates increases in the level of

rent. Berger (2000) presents more results on the land and water market issue. Informal annual rental contracts do not offer an incentive to invest in perennial crops and water-saving irrigation techniques. As a consequence, the potential of the market to efficiently

reallocate resources among farm holdings is not exploited under the present conditions by far. In special scenarios, with a high share of land and water purchases, diffusion speeds up significantly and income increases. Much more research seems necessary to improve our understanding of how efficient land and water markets emerge, as Vogelgesang (1996) points out.

8. Conclusions and outlook

After several decades of government regulations, most agricultural and development economists now share the conviction that decentralisation, innovation and market solutions can help to overcome the problems of the "critical triangle of development" (Vosti and Reardon, 1997). As a consequence, dynamic modelling concepts are required which allow the extension of economic analysis to market-driven innovation, resource use changes and structural evolution.

The study presented here has shown that a spatial multi-agent approach offers an exciting opportunity to model heterogeneous economic behaviour and policy responses from the farm-households' viewpoint. The inclusion of inter-household linkages makes it possible to model economic phenomena in which macrobehaviour emerges from micromotives, as Thomas C. Schelling (Schelling, 1978) has put it in his 1976 renowned book. Such phenomena are, for instance, the diffusion of multiple innovations, transactions on imperfect land markets, the use of water for irrigation and structural change in the farm sector.

A spatial multi-agent model is applied to an empirical question in Chile in order to test its applicability. The simulation scenarios help to explore the possibility space for regional agricultural development in the context of the Mercosur agreement. The traditional farm sector strongly opposes the trade agreement as it expects severe income losses. The model results indicate that Mercosur offers, in principal, higher farm incomes through innovation and would additionally increase on-farm labour intensity. However, if frequency-dependent diffusion processes are considered, modern farming practices (except perhaps, supplier contracts with the agro-industry) will probably

not reach traditional farmers in a reasonable lapse of time. On the contrary, the model suggests that structural change will occur as traditional farmers will experience persuasive 'pull effects' to leave the farm business. On the other hand, their income situation probably would not have improved significantly if the trade agreement had not been signed. Therefore, one might regard traditional farmers as relative but not absolute losers of Mercosur. A follow-up study based on an improved empirical data set will aim at verifying these results.

The model consists of an economic and a hydrologic component bound into a spatial framework. The integration of economic and hydrologic processes facilitates the consideration of feedback effects in the use of water resources. Although not presented specifically in this paper, land use changes can easily be predicted. The model's source code is written in the C++ object-oriented programming language and permits modular extensions to include ecological constraints or to create interfaces with GIS-applications.

Fully integrated economic and ecological models for policy development and evaluation remain an ambitious undertaking. In my opinion, the predictive capacity of such models will be mainly restricted by their inherent assumptions with regard to human decision-making rather than by ecological parameters. Spatial multi-agent models acknowledge the fact that regional land use emerges from decentralised human decisions. Thus, they can capture essential features of human–nature interaction. They are built on concepts of microeconomic theory that are typically lacking in the current land-use models. In particular, they make it possible to consider the introduction of improved land use practices as a farm investment decision to cope with natural resource degradation. As argued by various authors, viewing land-improvement as exogenous technological change may lead to misleading policy recommendations and certainly to an under-emphasis on farmland investment as a policy issue. Further testing of this model class and the incorporation of integrated ecological and economic modelling approaches is called for. The initial results suggest that once the practical problems of combining different types of models are solved, GIS-based integrated multi-agent models will become a powerful tool for policy analysis and natural resource management.

Acknowledgements

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