Modeling Land Use with Multi-Agent Systems
Perspectives for the Analysis of Agricultural Policies

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Abstract. This paper addresses the adequacy and perspectives of multi-agent system (MAS) models in the context of policy support for agricultural policy makers. The paper starts illustrating what MAS are and how they may be used. The general presentation is followed by the description of an exemplary spatial dynamic model of a large number of interacting farms (agents). This model is simulated for different policy scenarios and farm sizes. The results are analyzed with regard to the farm structure, land use, efficiency, and farmers' incomes. It is concluded that policy analysis should not only address problems of price distortions. If agricultural policies affect structural change in the way the simulations show, the dynamic efficiency and income implications may be much more severe. In particular, well meant subsidies may in the long run create a dependency on further support.

Keywords: multi-agent systems, policy analysis, structural change, path dependence.

1. INTRODUCTION

In the last decades the contents of European agricultural policy have changed significantly. This has several reasons. One reason is the transition of the Central and Eastern European countries. The transition has shown what happens if markets and institutions fail. Value chains broke down and many farms had to struggle for survival. Besides, some very interesting phenomena emerged. Although often declared as dead, in many countries previously collective farms and their successors still dominate the agricultural sector. Moreover, there is a kind of asymmetric behavior. The successors of previously socialist farms operate differently from newly and re-established farms. For instance, the successors of the Eastern German collective farms operate much more labor intensive. It seems that many of them strive for job maximization rather than for profit maximization (cf. Balmann et al. 2000). Obviously, the transition process is path dependent, meaning that we should not expect a convergence toward what might be expected under comparative static conditions. Hence we have to understand transition as a process that heavily depends on history and that occurs far from equilibrium.

Another reason for changing political topics is the increasing globalization and liberalization of trade. For many Western European farmers this has already lead to significantly lower prices which have partly been compensated by direct subsidy payments. But the agricultural budgets of the EU and of most of its member states are limited, too. Particularly with regard to the upcoming EU-enlargement, it can be expected that the amount subsidy payments will decrease significantly. This may lead to considerable structural adjustments if not a kind of 'transition' of the EU agriculture. At the same time, policy makers rediscover (after a long period of interpreting the agricultural sector rather as a planned economy than as a market economy) that farmers are actually entrepreneurs. The politicians increasingly recognize that structural change is not just an evil but also offers a chance to make European agriculture competitive. Moreover, we find despite or because of the globalization an increased attention to the principle of subsidiarity. This means that local institutions receive more competence.

Taking these developments seriously means that policy will increasingly address topics that have to with disequilibrium, dynamics, and locality. And one question will be, whether policy advisers have methods and tools which are appropriate to tackle these topics. Another question is, whether the present methods really make use of the changing opportunities. For instance, Information Technology and Geographical Information Systems allow for much better and more differentiated data. Since 'Moore's Law' is still valid, computing capacities increase (more than) exponentially. Last but not least - and this is not independent of increasing computing capacities - some new modeling approaches have been developed that have in common to start 'from the bottom up', meaning that they are highly disaggregated and explicitly consider the local interactions of individually behaving agents. Modeling approaches of this type belong to the class of multi-agent systems (MAS) or artificial societies.

In the remainder, it will be explained what MAS are, how they work and how they may be used in the context of policy modeling. Then, based on this approach an exemplary spatial model of an abstract agricultural region will be presented. Finally some explorative policy simulations of this model are presented and conclusions are drawn.

2. MULTI-AGENT-SYSTEMS

Multi-agent systems (Ferber 1999, Franklin/Graesser 1996) or artificial societies (Epstein/Axtell 1999) consist of a number of interacting autonomous entities which are understood as agents. Russell and Norvig (1995, page 33) have defined agents as follows:

"An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors."

This is a very general definition. Accordingly, agents may be persons, computer programs, or even thermostats. In a more differentiated way, Franklin/Graesser (1996) characterize agents according to their properties (table 1). Some properties are common to all agents. Agents are reactive, they act autonomously and goal-oriented, and agents sense their environment steadily. In addition, agents may have some particular properties, like the ability to communicate with other agents, learning, mobility, and flexibility. They may even have a particular personality and show emotions.

Table 1: Classification of agents (Franklin/Graesser 1996)

Property	Meaning
reactive	responds in a timely fashion to changes in the environment
autonomous	exercises control over its own actions
goal-oriented	does not simply act in response to the environment
temporally continuous	is a continuously running process
communicative	communicates with other agents, perhaps including people
learning (adaptive)	changes its behavior based on its previous experience
mobile	able to transport itself from one machine to another

To illustrate the application of MAS in economics, table 2 presents a classification and examples of multi-agent systems. Accordingly, there are two main fields of applications: operations research and systems analysis. Regarding the first field of application, a number of techniques has been developed on the basis of MAS to solve complex optimization problems, like artificial neural nets and genetic algorithms. Because most of these techniques have become standard in operations research they will not be explained here in detail.

More interesting for the purpose of this paper is the use of MAS in applied systems analysis. Here a number of rather prominent examples can be found in the economics literature. They can be classified according to the behavioral foundation of the agents. For instance, Schelling (1978) studied the migration dynamics of a spatial neighborhood of individuals belonging to different social classes. In Schelling's model, individuals stay or move according to certain rules that represent particular preferences. The model is able to show how social clusters or even 'ghettos' may evolve as a result of segregation phenomena. Another prominent example of such rule-based MAS are Axelrod's (1984) computer tournaments. In these experiments a number of computer programs played an iterated Prisoner's Dilemma game against each other. These experiments led Axelrod to the famous result that a strategy called TIT FOR TAT which is mainly based on reciprocity is highly successful in repeated social dilemma games.

Although rule-based agents can have empirical and theoretical support, they often lack a direct economic rationale. More sophisticated are agents with a normative behavioral foundation. An early example of a normative MAS in agricultural economics is the recursive programming approach developed by Day (1963) that considers a number of interacting farms, each representing a particular farm type. A fundamental extension of this approach can be found in Balmann (1997). In this approach - which will be presented in some detail in the following section - an agricultural region is represented as a spatial grid with each cell representing a parcel of land. Farms are located on some of these parcels.

Table 2: Classification and examples of multi-agent systems

Goal	**Problem solving / Optimization**		**Systems analysis**		
Agent characteristics	decentralization	solution competition	rule-based behavior	normative behavior	artificial intelligence
Examples	<u>general:</u> artificial neural nets cellular automata	<u>general:</u> genetic algorithms evolutionary strategies and systems	<u>special:</u> Conway's 'Life' Schelling (1978) Axelrod (1984)	<u>special:</u> Day (1963) Balmann (1997) Berger (2000)	<u>special:</u> Arifovic (1994) Axelrod (1997) Balmann (1998) Balmann/Happe (1999)

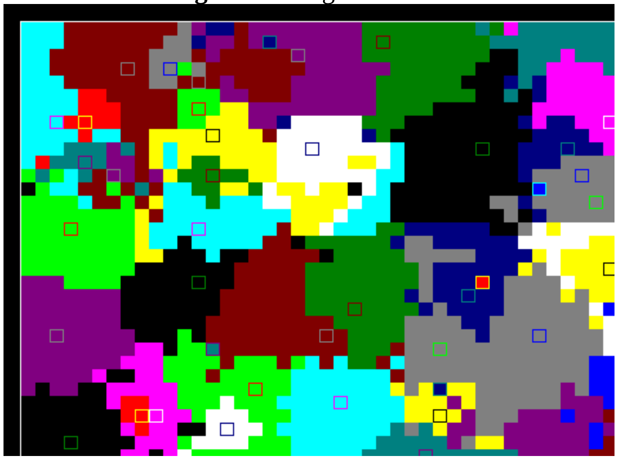
The farms aim for income maximization and compete on a land rental market. Each farm can engage in different production and investment activities, rent land, employ additional labor etc. Moreover, new farms can be founded and existing farms can close down. Originally, this approach was used to study endogenous structural change (Balmann 1997, 1999).recent years, a further conception of a behavioral foundation of individuals in MAS has been developed. Instead of a rule-based or a normative behavioral foundation, individual behavior is derived using artificial intelligence methods. For in Instance, Arifovic (1994) studies the dynamics of a Cobweb model in which a number of producers (a population of agents) determines their output by using a genetic algorithm (GA). In the search for solutions to a problem, GA employ the basic operators of biological evolution: selection, recombination (crossover) and mutation, which are applied repeatedly to a population of genomes, each representing a possible solution. These genetic operators not only determine how solutions are propagated into the next generation, they are also capable of generating new, possibly superior solutions. In Arifovic's study, the GA successfully identifies the Cobweb-equilibrium. Apart from market analyses, GA have also been used to study game theoretic problems (e.g. Dawid 1996, Axelrod 1997). Axelrod (1997) applied GA to study iterated Prisoner's Dilemma games. In Axelrod's study GA generated strategies that show key elements of the famous TIT FOR TAT strategy which proved to be most successful in his 1984 computer tournaments. Balmann (1998) and Balmann/Happe (2000) apply GA to a spatial land market. Both studies come to the conclusion that (under comparative-static conditions) limited market access has some distributive effects if it is compared to situations with unlimited access to the land market. Oligopolistic behavior however is limited to very restrictive conditions.

Although a number of interesting applications of MAS exists, one may still ask, what is so particular about them. The first point is that these approaches are very flexible with regard to the parameter settings of a model. On the level of the individual agent one can consider bounded rationality, heterogeneous goals and skills. Moreover with regard to the model's framework, one can consider non-convex functions and imperfect markets. The main reason for the flexibility regarding the assumptions is that the use of decentralized decision making allows to avoid the problem that the required computing resources increase unacceptably with an increased model size and complexity, i.e. MAS avoid problems of NP-completeness. The disadvantage however is that such MAS do not ensure global optimization and hence they are, for instance, not in accordance with the conception of unbounded rationality. Rosser (1999) even argues that bounded rationality is inevitable in complex models. A second point is that MAS allow for self-organization phenomena such as particular emergent structures like flocking birds or a laser beam. These self-organization phenomena include not just complex structures but also complex dynamics; dynamics that may include for instance persistent states far from equilibrium and multiple-phase dynamics (cf. Day/Walters 1995). Last but not least MAS allow in a very direct way the consideration of space, and hence they are virtually predestinated for agricultural and environmental research.

3. THE MODEL

Before in the remainder some policy simulations are presented, the model is outlined: Imagine taking a bird's-eye view on an idealized agricultural region in which land is divided into parcels of a fixed size like on a chessboard. Except for the spatial ordering, land is homogenous. It can be used for arable and for pasture farming. Furthermore, several farms operate in this region. The parcels on which the farmsteads are located are surrounded by a highlighted border. Each parcel rented by a farm has the same color as the farm. Then, this agricultural region might look like figure 1.[1]

Figure 1: Usage structure



The region consists of 900 to 6400 quadratic plots of 10 ha each. According to this model, every one of up to 225 farms only owns the plot on which it is located on. The farms have to be understood as agents. They act autonomously in a way that they try to maximize their individual household income. They can engage in 10 different agricultural production activities (e.g. dairy, cattle, hogs, sows, arable farming, pasture land) and they can invest in 15 different assets (differently sized buildings for various activities, machinery of different sizes). These investment alternatives allow for economies of size, i.e. with increasing size, labor is used more effectively and average acquisition costs per unit decrease. For instance - and in accordance with a number of

[1] The model is presented in detail in Balmann (1997).

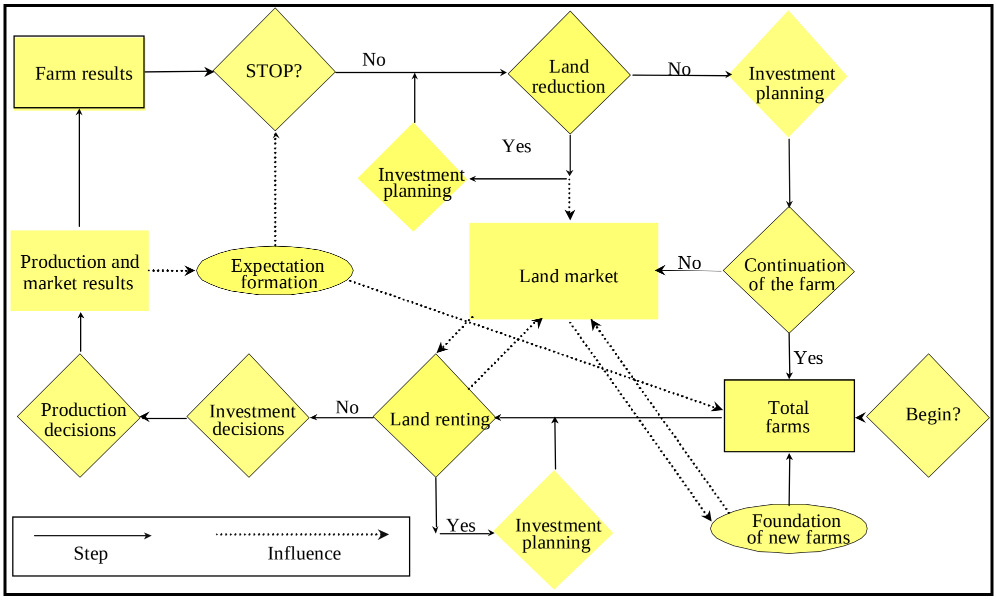


Figure 2: Flowchart of the program (according to Balmann, 1997)

empirical studies (Kirschke et al. 1998, Helmcke 1995, Peter 1993) -, it is considered that in cash crop production, economies of scale exist up to a size of 400 ha. In addition to the different production and investment activities, the farms can use their labor and capital for off-farm employment as well as they are allowed to hire in additional labor and to make debts. Additional land can be rented on a pure rental market and parcels can be disposed to the rental market. Farms can give up farming and new farms can be founded.

Although all farms act autonomously and can evolve heterogeneously in many variables (e.g. equity capital, liquidity, debts, asset structure, rental contracts) they all follow the same decision rules and expectations. Moreover, there is no difference in management abilities and the technical constraints. All decision making routines are based on adaptive expectations. Production activities are optimized by Linear Programming. Investment decisions are based on comparisons of expected annual net present values. If a farm invests, this has an impact on the farm's production capacities for the lifetime of the asset (machinery 10 periods, buildings 20 periods). The same holds for the capital stock that depends on previous investments as well as on previously gained profits. A farm closes down if it is either illiquid or if the farm's expected profit does not cover the opportunity costs of the factors that are owned by the farm-household. New farms are founded stochastically. The foundation probability depends on the number of free plots and on average farm size. This has to be understood as a kind of trial and error procedure. Hence, each farm's decision making is defined in a way that can be called myopic or bounded rational. Although the farms are rather smart with regard to the applied optimizations techniques, the farmer's cognitive abilities are limited. For instance, the they are not able to communicate with their neighbors and hence they are not able to use machines jointly or to merge.

The model can be understood as a complex distributed recursive programming approach that is simulated for a number of periods. In each period, all farms have to decide simultaneously on investments, land rentals, and production activities. For computational reasons the farms' decision making routines are ordered and embedded in the program flow shown in figure 2.

The farms are linked together via the land market. A farm can increase its acreage either if there is free land that is not used by another farm or if other farms reduce their acreage. The allocation of free land takes place in iterative auctions. Farms make offers according to their marginal productivity of land and their transport costs to the next free parcel. All offers are compared and the farm with the highest bid receives the plot it wishes. Then all farms make new offers that are compared again and so on. The auction stops if there is no more land available or if there are no positive offers. The rental price for any parcel that is newly allocated in a particular period is tied to the offer at which the last plot was allocated.

Table 3: **Policy scenarios**

	Small farm initialization (≈ 40 ha)	Large farm initialization (≈ 400 ha)
Reference scenario • gross margins decline at the rate 0.8 % p.a.	X	X
Price policy • gross margins decline at the rate 0.4 % p.a..	X	X
Transfer policy • gross margins decline at the rate 0.8 % p.a. • annual lump sum payments of DM 5000 per family worker	X	X

The farms are also affected by developments on product markets for the activities that are considered. Product prices may change according to regional production activities. However, because only a small region is simulated, it is assumed that the demand elasticities are rather high. Furthermore, it is assumed that the gross margins of the main agricultural activities decrease by 0.8% each period. This is done to induce a need for structural change. A more realistic approach would probably be the implementation of increasing opportunity costs for labor and technological progress into the model.[2] However, if we are interested only in qualitative results, this assumption should be admissible. To avoid inconsistency when using the adaptive expectations approach, the farms are considered to anticipate this trend for their periodical production decisions. To capture the diminishing terms of trade for long-term investment decisions, future net yields are discounted with an additional periodical rate of 1.5%.

To consider the effects of sunk costs, it is assumed that the acquisition costs of assets are totally sunk after an investment was undertaken, i.e. the opportunity costs of assets are zero. Furthermore, it is assumed that each farm is handed over randomly to the next generation with a probability of 5% per period. Then, for the decision whether to close down the farm, the opportunity costs of labor owned by the farm-household are considered to be 15% higher (≈ 5200 DM per person and period). If the farm continues, opportunity costs for non-farm use of labor remain at the lower level, since this is understood as an investment into agricultural training which reduces the chance of a profitable off-farm employment.

All models are simulated for 50 periods with one period representing one year. The initialization occurs stochastically. The data used are derived from farm management data samples published for the German agriculture. However, since the aim of the simulations is not to be perfectly realistic, the input data should be understood as a kind of stylized data.

4. POLICY SIMULATION

4.1 Policy Scenarios

To study different policy regimes three different scenarios are compared (cf. table 3). A reference scenario with decreasing gross margins as described is compared to a price policy and a transfer policy. The price policy scenario can be understood in the way that the government intervenes into the market, so that prices decrease less quickly. The transfer policy has to be understood in the way that the government does not intervene into the market, but supports farmers by lump sum payments for non-paid labor, i.e. for farm family labor. Both, the reference model and the alternative scenario are simulated for two initially different average farm sizes. In the first case, the average acreage is about 40 ha, in the second case, the average acreage is about 400 ha. This allows to compare the policy implications for a small farm initialization with the implications for a large farm initialization.

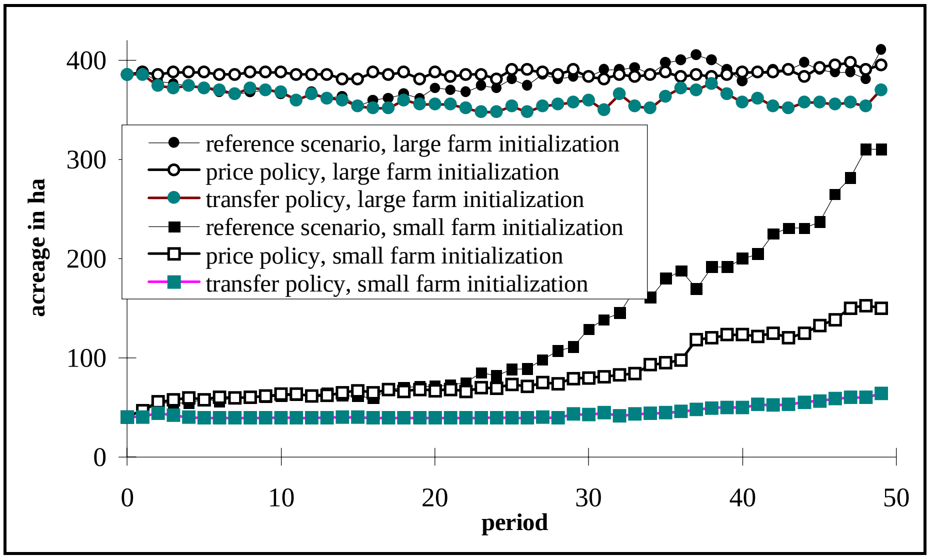


Figure 3: The evolution of the average farm size

[2] For an explicit consideration of technical progress cf. Berger (2000).

4.2 Results

In general, the defined policies may affect the farms with regard to different aspects. Besides the question of what farms produce, the policies may affect the farms' profitability and whether they remain in the sector. Thus the policies may influence structural change. This is indeed the case and it is shown by figure 3 with regard to the evolution of the average acreage per farm. Accordingly, the policy impact is relatively small for the scenarios in the case of a large farm initialization. In the small farm case however, the policy impact is much stronger and increases with the number of periods. Obviously, the price policy and the transfer policy in particular inhibit structural change.

The inhibition of structural change in the case of the small farm initialization is also shown by figure 4. In the reference scenario land use is dominated for the first 15 periods by farms with an acreage of not more than 100 ha. These farms

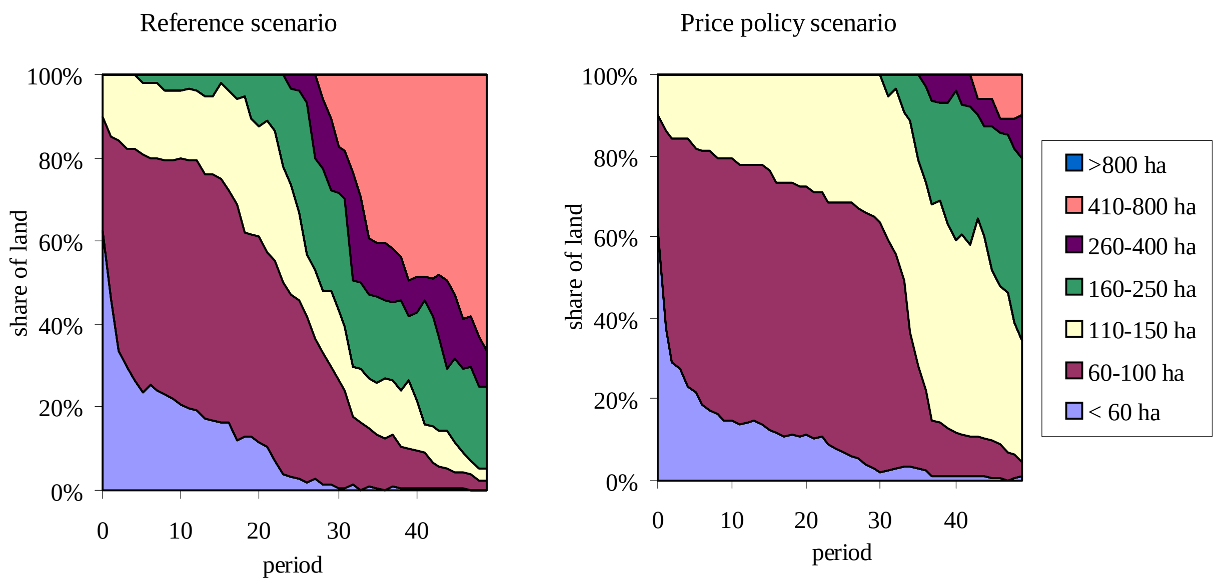


Figure 4: Cumulated shares of acreage for different farm size classes (small farm initialization)

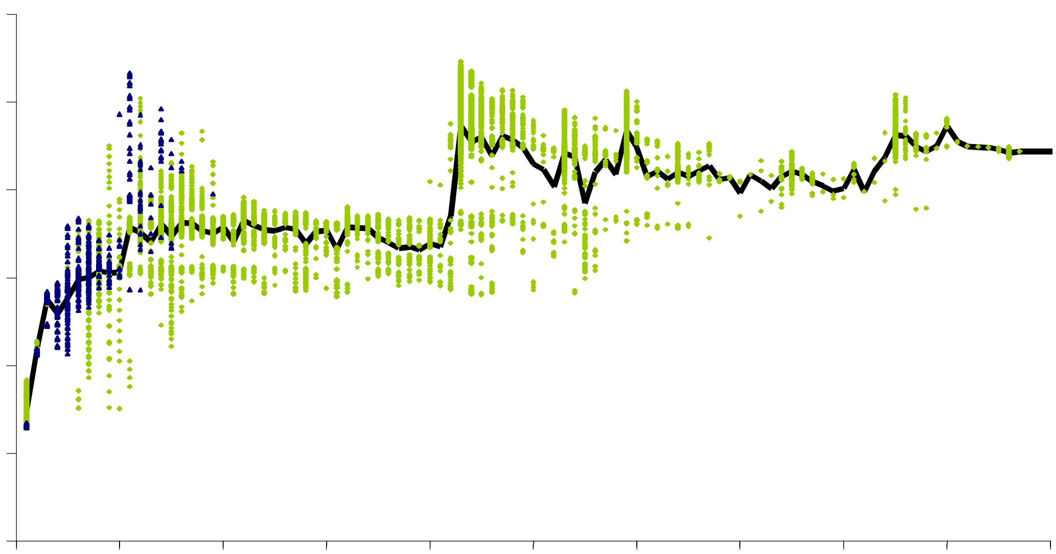


Figure 5: Economic land rent for simulations of the reference scenario*

* The data is price corrected for period 0 assuming that land productivity declines. The peaks result partly from the indivisibility of assets and an approximation of the assets depreciation. The latter leads in some periods to an overestimation in others to an underestimation of the economic rent.

are not able to exploit economies of scale. For illustration, figure 5 shows the economic rent of land obtained by the different farms in the different periods and which is computed as the net farm income minus the opportunity costs of labor and capital input. Accordingly, farms with less than 100 ha face significant increasing returns. As figures 4 and 5 show, for the case of the small farm initialization only a few farms achieve a farm size of 400 ha and more and are able to exploit economies of scale. According to Balmann (1999) this result implies that structural change has to be understood as being path dependent (Arthur 1989) with inferior farm structures becoming possibly a persistent phenomenon.

According to our simulations, subsidies amplify this problem. This is illustrated by figure 6. Particularly severe are the policy impacts for the small farm initialization. The transfer policy causes strong efficiency losses which have to be explained by deficits in structural adjustments. Lump sum payments to farmers create barriers for inefficient farms to exit the sector. Since the large farm initialization displays already in the beginning an efficient farm structure, the transfer payments do not matter. The efficiency impacts of the price policy have to be seen more differentiated. For the first 20 periods there are no significant efficiency losses. However, after about period 20 efficiency losses arise and increase steadily. On the one hand this is a result of price distortions, which affect the small and the large farm initialization. On the other hand, in the small farm case it is a consequence of the inhibition of structural change. This effect becomes obvious, if one recognizes that in the reference scenario the economic land rents even increase despite of declining gross margins. There the evolution of land rents shows almost a close up to the scenarios with large farm initialization. For the price scenario this does not happen so strongly, i.e. the potential benefits of structural change are not exploited

Summarizing these results, policy analysis should (on the supply side) not just concentrate on price distortions. Probably even more severe are the policy impacts on structural change. Subsidies can slow down necessary structural adjustments. The remaining of non-competitive farms in the sector diminishes the opportunities of potentially competitive farms because the latter have less access to decisive inputs like land.

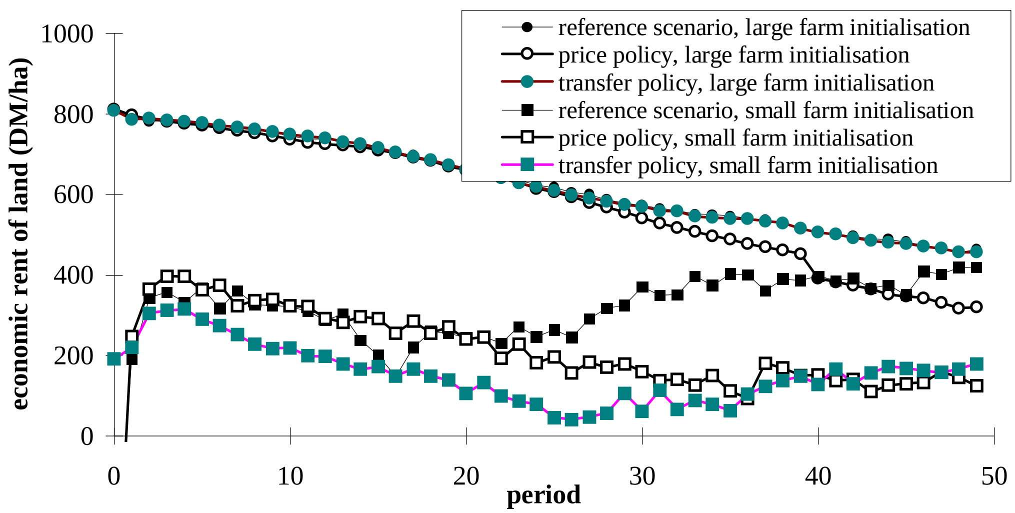


Figure 6: Policy impacts on efficiency
(Considering the devaluation of human and asset capital. Without subsidies.)

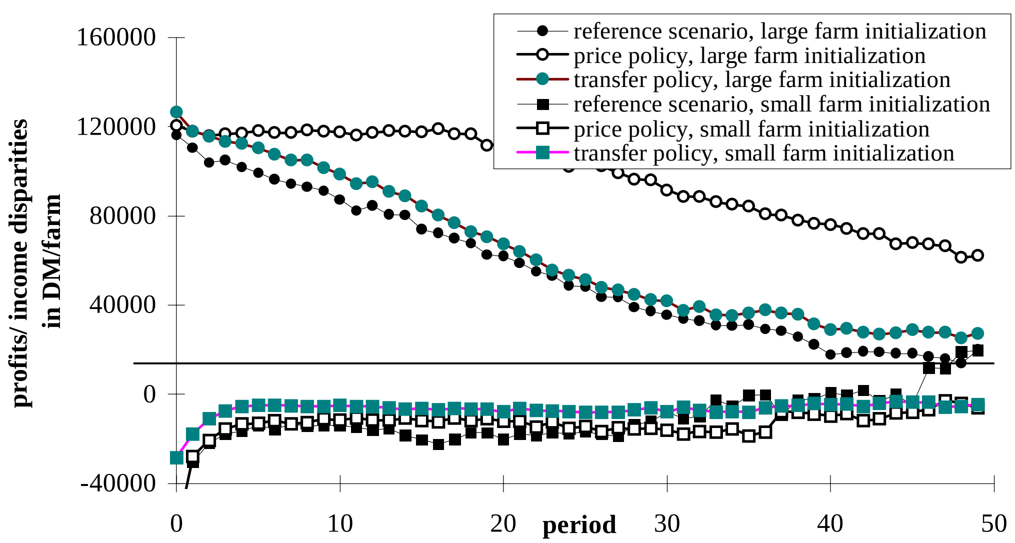


Figure 7: Policy impacts on profits (+) and income disparities (-)
(Considering realized wealth losses if farms are closed down.)

One may argue that the inefficiencies caused by the subsidies have to be understood as the price for income improvements of farmers which otherwise would suffer from income disparities, i.e. without subsidies the farmers' incomes would not cover the long-run opportunity costs of the used factors. Our simulations however show that this argument does not necessarily hold. According to figure 7, price policies are quite effective in large farm structures, but they are ineffective for small scale farming. Compared to the reference scenario, the price policy reduces the income disparities only slightly in the short and medium term. In the long run the price policy is even inferior compared to the reference scenario.

Although this result is quite surprising at the first glance, there is an intuitive explanation, which constitutes of different arguments:

- Firstly, considering a given farm structure, the price policy increases marginal and average factor productivity. For factors like labor and capital this means in general a positive income effect. But on the other hand, while the opportunity costs for labor and capital can assumed to be fixed or independent of the agricultural factor productivity, the opportunity costs of agricultural land are determined endogenously, i.e. they depend on the land productivity itself, the economic land rent. Hence, an increase in the land rents causes higher opportunity costs for land by increasing land prices and rental prices. This problem is particularly relevant because farms are the main users of agricultural land and the amount of disposable land is fixed.
- Secondly, sunk costs (or other arguments which induce fixed factors) often increase the shadow price of complementary factors.[3] If most farms in a region are affected by sunk costs and thus have high shadow prices of the complementary input land, this may result in high rental prices for land, too. Moreover, sunk costs lead to the effect that farms may continue production although their long run opportunity costs are not covered. In other words: Farms with sunk costs may continue production although income disparities exist.
- Thirdly, in the small farm scenario most farms operate facing increasing returns to scale, while in the large farm scenario many large farms operate with decreasing returns to scale. Increasing returns usually mean that marginal land productivity is higher than average productivity and vice versa. If now most farms operate with increasing returns, this may result in rental prices being higher than the average productivity and thus it may establish income disparities, too, whereas for decreasing returns profits are possible.

These aspects are reflected in table 4. Accordingly, the price policy increases rental prices. For the small farm initialization rental prices increase even more than land rents. In cases of a high fraction of rented land, this means that a large fraction of the productivity improvement goes to the land owners.[4]

Taking all these points together, it is questionable, whether subsidizing production allows for a sustainable reduction of income disparities as long as farms face increasing returns to size. And even if there are some positive income effects in the short run as it is displayed in figure 7, then these may slow down the natural process of structural change as a response to general economic growth and technical progress (Balmann, 1999). In such a case, besides the well-known comparative-static inefficiencies, subsidies for inputs and outputs also cause dynamic inefficiencies, because they prevent and inhibit structural change. The sector becomes locked into a situation that does not allow to exploit economies of scale. Then average productivity may be lower than marginal productivity and thus the economic land rent may be lower than the rental prices.

An interesting result displayed in figure 7 and table 4 is that direct transfers do also not prevent income disparities. The reason is that their linkage to the status as a farmer increases the threshold for farms before leaving the sector and therefore they also inhibit structural change.[5] Lump sum payments contribute to the occurrence of local optima and create particular growth barriers. As a result, transfer policies as they are implemented in the presented scenario may allow income improvements in the short term. But in the long

Table 4: Land rent, rental price and profits (average over 50 periods)

Initialization	reference scenario	price policy	transfer policy
small farms			
land rent	378	436	416
rental price	497	577	516
profit / income disparity	-119	-141	-100
large farms			
land rent	632	765	658
rental price	482	509	482
profit / income disparity	150	255	176

3 Since several decades the impacts of sunk costs have already been discussed under the topic of (quasi-)fixed factors. Cf. Johnson (1972).

4 If however most land is owned by the farmers, their incomes increase. Nevertheless income disparities may arise, but these rather result from the overvaluation of the opportunity costs for the farmers' land.

5 For example, a German farm household with an income of 50 000 DM from farming has an advantage in taxes and social security expenditures of approximately 10 000 DM over employee households with a comparable income (Forstner 1996). This means also that due to these transfer payments hired labor is much more expensive than family labor in agriculture.

run they prevent small farm agriculture to overcome the problem of unexploited increasing returns.

Summarizing these results one may conclude, that in the end a family farm dominated agricultural sector may suffer from well-meant policies formerly introduced to increase farmers' incomes. Particularly, when the agricultural sector faces a permanent deterioration of its intersectoral terms of trade, these policies may create a dependency on further subsidies which again lead actual structures away from efficient structures. In a situation such as in Western Europe where actual farm sizes are often far away from 'optimal' farm sizes, incentives that accelerate structural change by improving off-farm job opportunities for farmers may be a promising policy alternative to give farms the natural economic chance to participate in economic growth. Probably such a policy could increase the chance of the remaining farmers to make profits from entrepreneurship as well as it could increase the incomes of those who leave the sector. However, the realization of such probably more efficient policies faces some inherent problems, too. Neither do politicians (and agricultural economists as well) recognize optimal solutions in a better way than the farmers involved, nor are their interests necessarily coherent with those of the farmers. If an economy already shows high unemployment, job saving policies may hardly be realized. This is quite a practical problem that may explain, why e.g. the Common Agricultural Policy of the European Union and former EC does (and did) not create many incentives for farmers to leave the agricultural sector.

5. SUMMARY AND CONCLUSIONS

The presented simulations are based on a model that had been developed originally to analyze the particular dynamics of structural change. On the basis of this intention it allows to study long term policy effects. The obtained results shed some light on policy effects that have widely ignored by conventional policy analysis, such as dynamical efficiency and the resulting income implications. From this point of view, policy modeling on the basis of multi-agent systems seems very promising. On the other hand, the question is, how valid and how convincing the model and its results are from the perspective of politicians and economists. And indeed, there are some critical points:

- Firstly, one has to concede that the validation of such models is difficult and limited. Neither it is possible to recalculate all numbers, nor is it possible to compare the results directly with analytical and empirical results. Nevertheless, the results are surprisingly robust and did not change significantly during many revisions the model was undergoing the last eight years. Moreover, the results fit many empirical observations like slow structural change, persistently unexploited economies of scale (i.e. path dependence) and income disparities very well.
- Secondly, several of the model's assumptions (like for instance the existence of bounded rationality and economies of scale) and results (like path dependence and income disparities) are discussed very controversially in agricultural economics. Hence one may criticize that the model and its applications may only convince those people who are already persuaded of bounded rationality and increasing returns. A critic may argue that the model simulations just reflect what has been put into the model. But, this argument is too short-sighted. If the model's assumptions and results are in line with a particular economic argumentation this does not mean that it is trivial. Phenomena like bounded rationality, increasing returns, path dependence, and income disparities imply complexity and can often hardly be tackled analytically. Then the only opportunity is either numerical simulation or verbal and qualitative reasoning. The advantage of numerical simulation is that simulation allows to quantify the effects and to check the consistency of the argumentation. Herewith the simulations enable to find inconsistencies of the argumentation and to improve the theoretical arguments. They may even allow to develop hypotheses which enable promising empirical tests.
- Thirdly, multi-agent systems are usually high-dimensional and non-linear. Even for the user it is difficult to grasp the full structure of the results regarding their variability over the different agents and over time. Hence, it is far from trivial to mediate the model's assumptions and its results to third persons. Every presentation requires simplification and it may even occur that the more differentiated and sophisticated the presentation is, the more questions arise for the addressees. In the end, the analysis and presentation of the model results may require simplified models of the original model and its results. Sometimes it may even be useful to apply multivariate statistical methods to study the simulations' results.

Summarizing these points, it is clear that there are some problems with the use of complex MAS. But actually these problems should rather be understood as a matter of the research questions to which MAS are applied than one of the method itself. It is reality which is so complex. Models based on MAS allow just to consider and reflect this complexity. Hence, to renounce this method means often not to use a method that is able to grasp the complexity of the research question. Moreover, MAS have to be understood as a rather young field of research. The application of MAS allows to explore their opportunities and to learn about them. This is a valuable byproduct of a method which is a beneficiary of the increasing power of modern computers. The limits of such models are far from reached and they are steadily shifted further. This is particularly illustrated by looking at the recent dissertation of Berger (2000). Berger studied structural change and the diffusion of new technologies under the conditions of the MERCUSOR for a selected region in Chile. Therefore, he extended the basic version of the model presented here. For instance, in his ambitious model, the decision units, i.e. the farms, vary according to their adoption of new technologies, price expectations, and management capabilities. Moreover Berger considers communication between farmers by establishing social networks, he considered direct exchange of land between farmers, and last but not least, he included heterogeneous land qualities and a hydrological sub-model that simulates spatial water flows. These extensions as well as Berger's consideration of a much larger region was only possible by extensive use of modern computers.

To conclude, MAS offer the opportunity to look at economic and social processes from new and different perspectives. They allow to study questions which otherwise cannot be tackled at all or which require rather strong assumptions. Hence, MAS appear to be a promising tool for policy research. Their limitations will depend on the progress in information technology and on the resourcefulness of its users. Thus they are also a promising field of future research.

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