

Innovation as an alternative to migration? Exemplary results from a multiple-agent programming model applied to Chile

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Summary

Isolating the influence of environmental stress on migration in developing countries poses conceptual difficulties, as a great deal of complexity characterizes the underlying decision-making processes. Therefore, several authors object to any attempt at drawing a linear deterministic relationship between environmental degradation and population migration. Disentangling the complex decision-making process suggests a disaggregate micro-level approach. This paper presents a multiple-agent programming approach that explicitly captures the decision-making process of potential migrants at the micro-level. The model includes spatial interactions and environmental feedbacks, as well as a mechanism of cumulative causation, arising from inter-household linkages. A model prototype is empirically applied to a rural area in Chile, which is characterized by water scarcity and high potentials for both innovation and migration. Several simulation results demonstrate the type of information that the model generates for policy analysis. The results underline the importance of communication networks and favorable conditions for technology adoption. Innovation can then be an alternative to migration and has the potential to turn a sending region into a receiving region.

Key words: environmentally induced migration, integrated modeling, mathematical programming, multi-agent systems

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1. Introduction

Several authors have questioned a direct relationship between environmental degradation and migration. In her literature review, KLIOT (2001) argues that immediate causation is usually taken for granted but not accompanied by documented evidence. What is typically interpreted as forced environmental migration in developing countries is often an institutionalized mechanism to cope with resource scarcity. Households locate their members in different areas and labor markets so as to diversify risks that cannot be privately insured (STARK, 1991). Remittances may furthermore serve to finance investments in new technologies aimed at diminishing the household's dependency on fragile natural resources. Against this background, combining migration and innovation is a highly suitable household strategy, especially when households lack access to capital markets. Facilitating credit as a policy measure might therefore provide strong incentives for households to invest in innovations such as improved land use practices and to substitute for migration.

Usually, migration and innovation are associated with substantial structural changes in the rural economy and especially in agriculture. The number of farm households declines considerably, resulting in modified labor/land ratios. Land markets, as well as resource use efficiency, and finally local income levels are directly affected. The outcome of this complex adjustment process is not predictable in a straightforward way. Cumulative causation (or positive feedback) play important roles both for migration and innovation and impinge on the direction of the adjustment path. A conceivable outcome is a new equilibrium in the sending region, both in terms of environmental status and agricultural incomes. Another possible equilibrium outcome is unmitigated environmental depletion and total population displacement.

In the last decade, economists have intensively discussed such dynamic phenomena, usually referred to as multiple equilibria or path-dependency (COWAN and GUNBY, 1996; BRANDES ET AL., 1997). One implication is that policy measures can involuntarily lead to inferior development paths that are afterward difficult to abandon. Adjustment costs are then too high and cause a lock-in situation. HAZELL and FAN (2001) also point to the policy-relevance of this issue in the context of environmental stress, innovation and migration. Though innovation in agriculture is a key strategy for many environmentally fragile areas with growing populations, policy-makers should avoid inadvertently locking too many people into these marginal areas when long-term prospects are limited.

Building quantitative models to forecast the households' responses to environmental changes and to identify policy interventions leading to lock-in still remains a challenge. An ideal model would incorporate biophysical as well as socio-economic processes and capture the dynamic effects of complementary migration and innovation decisions. It should make allowance for the potentially path-dependent feature of adjustment; be capable of exploring the likely impacts of different technology and policy options; and thus generate useful information for policy formulation and analysis. Migration and several crucial environmental processes in agriculture – such as soil erosion, nutrient leaching and flows of irrigation water – are spatial phenomena. An ideal model would also be capable of considering the related biophysical changes in a spatially explicit manner. Integrated simulation models based on the multiple-agent systems approach are promising candidates to meet these criteria. The next section discusses in more detail the basic theoretical concepts of positive feedback in migration and innovation processes. Section 3 briefly introduces multiple-agent systems and explains how this modeling technique has been used in agricultural economics. Section 4 describes the implementation of a multiple-agent model for a rural area in Chile characterized

by water scarcity and high potentials for migration and innovation. Section 5 discusses some simulation results that show the model's applicability to policy-related research questions. The last section concludes with final remarks.

2. Environment, migration, and innovation

Isolating the influence of environmental stress on migration in developing countries poses conceptual difficulties, as a great deal of complexity characterizes the underlying decision-making processes. A multitude of factors and economic motives affect the households' choices among different alternatives of action. Typically, decisions have to be made in an information-poor setting under a considerable degree of uncertainty. Since information search costs are usually high, households have to rely and build their perceptions on rather vague judgments and the subjective experiences of others. Some authors, cited in KLIOT (2001), therefore object to any attempt to draw a linear deterministic relationship between environmental degradation and population migration. Rather, a disaggregate micro-level approach is called for to disentangle the complex decision-making process.

FISCHER ET AL (1997) provide a comprehensive account of micro-economic research on migration decisions. To understand how households manage the information problem and how they arrive at their decisions, a behavioral model based on the theory of investment under uncertainty has been broadly applied (DIXIT and PINDYCK, 1994). As with long-term investments in capital goods, migration and innovation typically imply high initial costs and uncertain later returns. Households compare the perceived costs and benefits of all possible investments according to their own decision rules. Following STARK (2001), three fundamental motives underlie the household decision rules in this context: (1) potential increase of income; (2) relative deprivation, i.e., the household's economic status compared to other households in the reference community; (3) personal desire or preference for migration or innovation independent of direct economic considerations. Though household decision-making is evidently a dynamic process, most studies on migration take a comparative-static view so as to reduce the complexity of analysis. For future research, FISCHER ET AL (1997) suggest putting more emphasis on the dynamic repercussions that earlier household decisions have on the determinants influencing the decision-making process of others.¹ The remainder of this section explains that one possible way of taking into account these dynamic effects builds on a model of information exchange, which has been, until now, applied separately to migration and innovation.

FAIST (1997) describes the sociological concept of chain migration and illustrates the underlying mechanism by means of an S-shaped migration curve. Pioneer migrants, who maintain the social ties to their home community, are crucial for communicating the working and living conditions abroad. If the information they communicate is positive, this information contagion can start off a kind of self-sustained process leading to more and accelerated out-migration. The pioneers encourage their relatives and friends to migrate; these encourage other relatives and friends to migrate, and so on. The terms "pioneers" and "information contagion" are also well-known to agricultural economists, though in a slightly

¹ FISCHER ET AL. (1997) name two related fields of research that are also to a great extent unexplored: the behavioral dynamics of the migration decision itself – when, why and how often do individuals ask themselves whether to migrate –, and the formation of individual expectations about disadvantages and advantages of migration – how is information gathered and up-dated. This paper focuses only on inter-household linkages because this approach can be grounded on empirical parameters and implemented in a straightforward way in a computer simulation model.

different context. COCHRANE (1979) developed a model of technical and structural change in agriculture, where farmers learn from the pioneers' experiences in new technologies. Since the "innovators" enjoy some additional profits through technology adoption, their competitive advantages on the land market improve over the "laggard" farmers who will then gradually be driven out of business.

Both approaches base themselves on the uncertainty-reducing effect of new information when a few pioneering households start engaging in a novel activity.² The location of particular households within the chain of information contagion can be estimated empirically with the so-called network threshold approach (ROGERS, 1995). Making this communication effect endogenous to a micro-economic model of migration and innovation decisions would then enable forecasting of the likely impacts of conceivable environmental and policy changes. Accordingly, the idea that will be developed below in more detail is to extend COCHRANE's approach of agricultural change by explicitly including migration, capturing the decision-making processes of all households involved, and applying this empirically-parameterized model to a potential sending region. As stated in the introduction, migration and several crucial environmental processes in agriculture are spatial phenomena that impinge on the choice of land and water use options. The biophysical environment in which potential migrant households interact should therefore be captured in a spatially explicit manner. A very effective way of encoding this integrated spatial model in computational form is employing a multi-agent system. The next section briefly introduces this novel modeling technique and describes how it has been used for the simulation of land-use/land-cover change.

3. Agent-based modeling of land-use/land-cover change

Multi-Agent Systems (MAS) is a quite recent concept, originated in the computer sciences, that has rapidly diffused to other disciplines and is now more broadly applied to the analysis of complex systems. In the social sciences, MAS gave rise to a completely new field of research, namely, computer simulations of the social mechanisms that supposedly underlie human societies (GILBERT and TROITZSCH, 1999). A prominent example is *Sugarscape*, an artificial society of simple computational agents that harvest and consume sugar, trade it with a second resource, migrate, reproduce and may even engage in tribal wars (EPSTEIN and AXTELL, 1996).

MAS is also of great interest for the empirical study of human-environment interactions, because it is highly suitable for representing interlinked socioeconomic and biophysical processes. PARKER ET AL. (in print) review current applications of MAS to the modeling of human resource use decisions and subsequent land-cover changes. They define agent-based models of land-use/land-cover change as consisting of two key components. The first component is a cellular model that represents the landscape under study. This cellular model may draw on a number of specific modeling techniques such as *cellular automata*, *spatial diffusion models*, and *Markov models*. The second component is an agent-based model that represents human decision making and interactions. It consists of autonomous decision making units (computational agents), an environment through which the agents interact, rules that define the relationship between agents and their environment, and rules that determine the sequencing of actions. An agent typically represents a land manager who combines individual knowledge and values, information on soil quality and topography (the biophysical landscape

² This uncertainty-reducing effect figures importantly in different strands of literature such as technology diffusion (METCALFE, 1988), path-dependence (COWAN and GUNBY, 1996), and social networks (VALENTE, 1995).

environment), and an assessment of the land-management choices of neighbors (the spatial social environment) to calculate land-use decisions. The model agents may also represent higher-level entities or social organizations such as village assemblies, local governments, or a neighboring country. In the place of differential equations at an aggregate level, agent-based models of land-use/land-cover change represent the decision rules, such as income maximization or minimum subsistence levels, of each human actor, their environmental feedbacks, and carryover of spatially distributed resources.

The particular strength of agent-based models is their suitability to account for heterogeneity and interdependencies among agents and their environment. The cellular model component provides a common spatial identifier to link biophysical simulation models with socio-economic decision models. Agent-based models are generally implemented via object-oriented programming languages, which provide an efficient and transparent way of organizing large amounts of data to handle complex model dynamics. Furthermore, their high degree of flexibility makes it possible to incorporate a wide range of agent decision rules. Especially in agricultural and resource economics, *mathematical programming* has been widely used to represent the microeconomic decision rules of real-world land managers (HAZELL and NORTON, 1986). Mathematical programming, in a nutshell, is a constrained optimization technique. It maximizes a function of independent variables (here: hectares of land put under certain land use types) subject to *a priori* limitations on the allowed values of independent variables (for example: hectares of land must be a nonnegative number and all farming activities together must not exceed the total area of arable land). The function to be optimized (the “objective” function) can reflect different decision rules. If for example profit-maximization is sought for, it corresponds to the sum of profits of all available land use activities. The solution to the programming problem is then the profit-maximizing (“optimal”) choice of land use activities. In principle, all conceivable decision rules can be formalized in mathematical programming so as to reflect other and more complex goals and decision rules of real-world land managers.

The combination of mathematical programming – to mimic farmer’s decision making – and agent-based modeling has been pioneered by BALMANN (1997). He developed a hypothetical farm sector model and showed the theoretical effects that the spatial distribution of farms has on land rents and the speed of structural change in agriculture. As the next section shows, such combined agent-based land-use models allow to parameterize an integrated migration-innovation model with empirical data and to address the policy research questions outlined above.

4. Model implementation in Chilean case study

This section briefly sketches a prototype MAS application to a rural area in Chile with high potential for both migration and innovation. For a listing of model parameters and equations consult BERGER (2000). A summary of the model variables is given in **Table 1**.

Problem and research questions

As noted in the first section, agricultural intensification and, in particular, higher levels of efficiency in water and land use are key elements for improving the livelihood of rural households in potential sending regions. Both generally require some form of innovation, such as farm investments in superior land-use practices and irrigation methods, agricultural extension, and institutional changes. Several authors have argued that viewing land and water

use improvements as exogenous technical change can result in misleading policy recommendations and certainly to an under emphasis on farm investment as a policy issue. In line with this argument, the model focuses on the diffusion of water-saving irrigation methods in a watershed; the effects of innovation and migration on the farm structure; and the impacts of possible government interventions aimed at supporting farm-households to improve their resource use efficiency.

Methodological pre-considerations

Though currently only a prototype, the model is in principle designed to provide policy-relevant information, especially regarding the impacts of policy on different farm and resource user groups. By means of computer simulations, it should facilitate the exploration of suitable policy options and forecasting out-migration and natural resource use changes. This explorative and predictive purpose has clearly impacted the level of abstraction and complexity in the representational model. It works at a highly disaggregated level, since the phenomena under study – diffusion of innovations, change in farm sizes and migration – require the modeling of heterogeneous farm-households and inter-household linkages. The spatial context figures prominently – e.g. upstream-downstream water uses, local water and land markets – and therefore spatial relationships must also be included.

Accordingly, several socioeconomic and biophysical processes such as decision making and interactions of individual agents, land markets, migration as well as irrigation water flows and agronomic relationships are endogenous to the model. However, socio-political phenomena such as rule formation, group decision making, and institutional change are treated exogenously.

System under study

To test its applicability, the model was first applied to the Melado River Catchment in Chile with a size of about 670 km² and 5,400 farm holdings. Irrigation water is scarce and only sufficient for extensive cropping and livestock farming. An overall switch of production toward higher-value irrigation systems would require first the introduction of water-saving irrigation techniques and second the reallocation of water rights among farmers. Currently, many farmers grow traditional crops such as cereals with relatively inefficient irrigation techniques and accordingly make only limited use of their water rights. The situation might, however, change rapidly in the next years. In 1996 Chile signed an agreement with the South-American trade union “Mercosur” that will result in reductions of tariffs by 30%, on average, over a period of 17 years. As a consequence, relative prices in agriculture will change and considerably affect the profitability of different farming practices. The new market environment implies both strong incentives for shifting production systems toward high-value crops irrigated with modern water-saving technologies and disincentives for growing traditional crops with rather inefficient irrigation techniques. But it is questionable whether these incentives will also induce the traditional farm households to innovate and to modernize their farming systems. Instead, empirical studies based on household interviews have predicted a high potential for out-migration in this household group.

In order to capture the complete process of market integration in agriculture, the temporal period being modeled is 19 years – starting in 1997.³ To model the adjustment at the farm-

³ Choosing the starting point in potentially path-dependent systems may predetermine the development path and thereby affect the model forecasts. Numerical robustness tests with random parameters showed, indeed, the model’s sensitivity to starting conditions on the individual household level. On the level of household types,

level, disaggregated land use types in agriculture and forestry are being included: 5 soil types, 3 technological levels, and 160 cropping, forestry, and livestock systems. Since the catchment's farmers only employ surface water for irrigation, and other water uses do not figure importantly, the model concentrates on surface water flows in agriculture. The model limits itself only to the farm-households and non-farm landowners who engage in land and water markets and whose plots belong to different irrigation sections within the Melado water user association. Each resource user – or household to be more precise – is represented individually – i.e. the model is disaggregated to the farm-household level. Other real world agents – such as farm workers and *minifundistas* with farmland of less than 2.5 ha – are not included since they do not contribute significantly to the resource use decisions and market dynamics.

Model implementation

The spatial resolution at which the model operates is 158 * 158 m – i.e. the size of one grid cell is 2.5 ha –, and the time step is one month. This rather fine spatio-temporal resolution had to be chosen because rented farm plots are typically of this size, and crop water requirements are usually modeled based on a monthly time interval.

The model contains three basic functional types of agents that stand for *campesino* family farms, commercial farm holdings and non-agricultural landowners. Empirical analysis in Chile revealed that both holding types represent two distinct communication networks. In each network, five subgroups were identified corresponding to different positions within the chain of information contagion. The position of a particular household is measured by its network threshold, defined as the percentage of all other households within its reference group that must previously engage in a novel activity before the household eventually adopts this behavior (VALENTE, 1995). Innovators, for example, adopt a new technology when the percentage of adoption in their communication network is still low; they have low thresholds. Laggards with a relatively high demand for interpersonal information adopt the same technology only when the percentage of adoption is close to hundred percent; they have high thresholds. These empirically estimated thresholds can be used to predict the communication of information in similar decision problems (BERGER, 2001). The same applies, in principle, to migration decisions.⁴

The agent's decision rules, chosen to represent the behavior of real farm-households, are based on the general framework of maximization of expected utility. The household agents allocate their labor and land resources so as to maximize the expected household income over time. The decision model abstracts from intra-household bargaining and assumes a household head that behaves altruistically on behalf of all household members. In comparison with other decision models in the migration literature, this model is dynamic. The household agent decides on whether to move or to stay at the end of each year, after the harvesting is done. An entire agent household sells out all its assets and moves out of the region either because of

however, where policy impacts are usually evaluated, the absolute forecasted values differ, but 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).

⁴ To the author's knowledge, there is yet no empirical study available supporting the threshold model of adoption for migration. The Chilean model parameters for migration are therefore based on *ad hoc* values and tested with sensitivity analyses. The simulation results that will be presented below in the next section, are derived from a model specification with two sub-networks for innovation decisions but only one overall network for migration decisions.

earning differentials (voluntary migration) or insolvency (forced migration). Here, insolvency means the inability to attain a minimum subsistence income. Since environmental changes directly translate into production costs, the household agent attempts to anticipate them and forms expectations. The decision model captures some of the uncertainty of migration and innovation decisions by relating them to the experiences of network partners. Household members or entire agent families move to other locations or adopt new technologies when the expected increase in family income is positive and a sufficient proportion of peers in their network has previously moved or adopted. The dynamics of the agent's decision making is captured through comparisons of adoption levels for migration or new technologies with the agent's network threshold. In the Chilean model the decision rule at the agent level is as follows: (1) monitor the present adoption level and compare it with the individual threshold; (2) if the network threshold is reached, calculate the household's net benefits from adoption; (3) if the expected net benefits are positive, then adopt. By varying parameters such as network thresholds, expectation coefficients, and household-specific opportunity costs, different motives for migration and innovation can be implemented. If the model households, for example, compute the expected incremental income in relation to the average income in their reference group, the effect of relative deprivation is captured. As a special case, the model households may also behave according to the standard economic theory, which implies they have complete information and perfect foresight with respect to farm prices; maximize expected income; and migrate whenever their market opportunity costs are higher.⁵ As will be shown in the next section, comparing the standard economic scenario with frequency-dependent scenarios reveals multiple equilibria and potential lock-in and thus provides useful policy information.

Besides innovation and migration, the decision-making process of real world farmers also contains rather simple problems that are frequently repeated and involve much lower degrees of uncertainty. Such problems are, for example, choice of crops, distribution of water for irrigation, and renting of plots. Exchange of peer-to-peer information is usually not a prerequisite for decision making. Hence, representing these decision problems does not require network thresholds; maximization of expected income as in the standard economic approach will in most cases be a good approximation of real farm household behavior.

The representational model of decision making is encoded in computational form by means of a recursive whole-farm *mathematical programming* routine (HAZELL and NORTON, 1986). Each farm-household agent has its own objective function, resource constraints and updates its expectations for prices and water availability. A mixed-integer linear programming solver is used for the farm investment and land rental decisions. In this respect, the model has characteristics similar to the independent representative farm models described by HANF (1989). However, there are two important features that distinguish the present model from the conventional independent farm approach: (1) there is a one-to-one correspondence between real-world and modeled agents, that is, each single real world farm-household is represented by a single model agent; (2) several types of interactions among agents are endogenous to the model, such as contagion of information, exchange of land and water resources, and return-flows of irrigation water.

This one-to-one MAS representation facilitates the consideration of agricultural production at a very fine spatial resolution, as well as the representation of bilateral and direct interactions

⁵ To be precise, they almost behave like rational decision makers with perfect foresight. Since the model contains non-convexities, the employed decision making routines may not under all circumstances converge toward the global optimum. 'Market opportunity costs' refer here to the household income that could be obtained if the household closed down its farm and migrated to a new destination.

between agents. Including these direct interactions among agents broadens the scope of resource use modeling significantly because – apart from the frequency-dependent effects in migration and innovation – other economic phenomena that conventional models cannot easily address are now explicitly modeled.

First, as has been maintained above, migration and innovation affect the local land markets; in some areas the level of rent tends to rise, in others, to decrease. Around each plot being offered on the land market, internal transport costs from the plot to a farmstead shape a kind of “von Thünen ring.” As a consequence, only a small number of neighboring farmers compete for a plot, which may lead to excessive land prices when several farmers with high land productivity attempt to simultaneously expand the size of their farm. Internal transport costs thus impinge on the level of rent by limiting competition on the land market. Here, the model captures the agents’ location and internal transport costs through a raster-based geographical information system. Each grid cell corresponds to one farm plot held by one single landowner. This direct ownership representation was chosen to implement land and water markets in a spatially explicit way. Due to internal transport costs, only neighboring model agents compete for each offered plot. Finally the agent with the highest bid receives a particular plot, providing his bid is higher than the asking price.⁶

Second, feedbacks that stem from the spatial distribution of irrigation water flows are included in the model. Monthly return flows affect downstream water availability, and may force model farmers to temporarily undersupply their crops or even to abandon them completely. The model farmers then have an incentive to employ more efficient, water-saving irrigation technologies. In reality, water shortages usually hit downstream farmers harder than upstream farmers, because upstream farmers often take more water than their irrigation quotas allow. The model reflects either a perfect water allocation – the farm agents receive their quota of irrigation water exactly – or more realistically, at least in the Chilean context, deficiently enforced water rights where parts of the return flows are uncontrolled. The spatial interactions of the water resources system are represented at a much coarser scale than the ownership of parcels, because grid cells are grouped to hydrologic units of an average size of about 32 km².

Figure 1 summarizes the spatial data representation together with the heterogeneity, interdependencies and hierarchies of the model. There is spatial heterogeneity (soil quality, irrigation water supplies, ownership of land parcels and water user rights), technological heterogeneity (farming equipment of different technological levels), and social heterogeneity (different managerial capacity, several social networks). Interdependencies are spatial (return flows, land and water markets) and social (communication networks). The land cover/use and water supply of a particular grid cell are results of the decision-making process at the farm level, which reflects technical, financial and higher-level social constraints.

Verification and validation

Having calibrated the model to a base year, validation experiments were performed to test the model’s validity. As the model operates on various scales simultaneously, a previous aggregation of input data to one common level of aggregation was not necessary. This implies the thorough testing of its ability to approximate real-world observations on the micro-level (farm-households), meso-level (hydrologic units) and regional-level (river catchment). Since reliable remote sensing data were not available at that time, only aspatial statistical analyses

⁶ The agents base their bid on economic calculus and compute the parcel’s “shadow price” (BERGER, 2000).

were conducted that revealed a sufficient “goodness of fit”. Since the model has many degrees of freedom and contains highly recursive dynamics, extensive robustness experiments and statistical tests were also conducted. Finally, comparisons of performance with other models and expert validation helped to create trust in the model’s behavior and results.⁷

The often quoted advantage of the mathematical programming approach in merging different data sources was fully exploited (HAZELL and NORTON, 1986: 3). An extensive farm-household survey, in-depth interviews, social network analyses and results from farm trials were used to derive a consistent farm data set. Based on a water engineering study for the Chilean Ministry of Public Works, the hydrologic units, equations and model parameter were defined. Spatial data at the hydrologic unit level had to be disaggregated to plot level using a random data generator constrained by *a priori* information. The registry of the local water user association was consulted to assign water rights to model agents.

Technical aspects

The author developed the multiple-agent programming software for this study, drawing on BALMANN’s (1997) source code. The new source code is written in the C++ object-oriented programming language and 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.

Usually, encoding heterogeneity in the carryover of farm resources, different technical coefficients, interest rates, objective functions as well as storing spatial data poses difficulties in farm programming models. The object-oriented programming language, in contrast, allows a much more transparent organization of data and model dynamics. By implementing agents as objects, the computational model can be encoded in a clear modular form. Using an object-oriented programming language typically reduces model development costs and numerical difficulties. As HARRINGTON (1995) shows with the instructive example of a simple program for calculating debt servicing, the object-oriented implementation considerably increases the extendibility and portability of previous verified source code. The code of BERGER’s (2000) multi-agent model can therefore be extended relatively comfortably by ecological constraints or interfaces with GIS-applications, for example.

5. Discussion of simulation results

By representing the resource users’ own decision making in a spatially explicit way, the multi-agent model forecasts competing land and water uses over time and investigates in particular the role of innovation and migration in agriculture. Some simulation results that demonstrate the type of information the model generates regarding the following topics will be briefly discussed:

- What is the range of possible water and land use changes? How fast will water-saving irrigation methods diffuse?
- Will these innovations reach the traditional farmers? Will they generate additional incomes and induce them to stay?
- Will the situation on marginal lands deteriorate? Will the farm income on these lands change in comparison to the regional average?

⁷ More details on verification and validation are given in BERGER (2000).

- Under what conditions will migration increase or decrease? Can innovation be an alternative to migration?

Figure 2 shows the “possibility space” of water/land-use changes by comparing the frequency of several irrigation methods with different on-field efficiencies. The right-hand graph reflects a hypothetical situation without technical change, where farmers are reluctant to innovate and refuse any technology adoption.⁸ The left-hand graph reflects the boundary scenario of ideal technical change where the model’s farmers adjust smoothly as predicted by the standard economic models.⁹ Ideal technical change leads to a sizeable expansion of modern water-saving irrigation within ten years. Almost half of the irrigated area would then be efficiently irrigated; the rest are soils of poor quality where only extensive rain-fed land uses, such as grasslands and forest, are profitable. In contrast, the middle graph shows the expansion of modern irrigation techniques under “bandwagon” conditions, that is, when the model farmers rely on interpersonal communication and learn from their peers’ experiences.¹⁰ The diffusion of water-saving innovations is then significantly slowed down and reaches only a sixth of the irrigated area over twenty years. Many model farmers with high network thresholds do not adopt these irrigation technologies, though they would under ideal conditions. One might therefore conclude that agricultural water use is locked into low efficiencies and could call for policy interventions to speed up the diffusion of water-saving innovations. In other scenarios, not shown here, the effects of different policy programs, such as the one demanded by the Chilean farmers association, were analyzed. The program includes special credit schemes to facilitate the adoption of water-saving innovations, public investments in irrigation facilities as well as fertilizer subsidies. A comparison of this program with other programs showed that temporary path-dependencies can eventually be broken down but may demand considerable financial resources.

Figure 3 shows the effects of technical change on the traditional farm households in both communication networks. Under ideal technical conditions, traditional households adopt water-saving innovations and almost double average family income as compared to the scenarios without technical change. As the lower left-hand graph indicates, they have no incentive to move and remain in the farming business. Under market conditions, however, the picture changes completely. In contrast to other household groups, technical change does not reach traditional households and many model households decide to migrate permanently. Approximately 25% of the traditional *campesino* and 75% of the traditional commercial households move out. Although traditional *campesino* and commercial households behave similar under bandwagon market conditions, they respond differently to policy interventions. For example, the program of the Chilean farmers association only slightly affects the average household income and the rate of out-migration of traditional commercial households. But the same policy intervention induces a notable response of traditional *campesino* households. The average household income rises to levels as high as under ideal technical conditions and out-migration increases significantly. The explanation is that traditional *campesino* households are relatively deprived through policy intervention because the average farm income of the more innovative households in their network groups increases more than proportionally. As a

⁸ This scenario is implemented by setting all network thresholds to hundred percent.

⁹ Here, smoothly means that interpersonal communication is ignored by setting all network thresholds to zero. Hence, this scenario corresponds to the so-called equilibrium diffusion concept that postulates *a priori* complete information sets (METCALFE, 1988). Differences in adoption behavior are explained by indivisibilities and minimum farm sizes.

¹⁰ The bandwagon scenario reflects the disequilibrium diffusion concept (METCALFE, 1988) and employs network thresholds as estimated in the empirical network study. See BERGER (2001) for more details.

consequence, the traditional *campesino* households with the lowest farm incomes move out and thereby raise the average income of the remaining households in this group.

Figure 4 indicates that the relative income of households operating on marginal lands will likely deteriorate over time. In the ideal technical scenario, the relative income of the mean *campesino* farm-household declines progressively and finally reaches only 50% percent of the regional average in this holding type. In the group of commercial holdings, differences in relative income are less pronounced but still amount to 15% percent. The relative deterioration of household incomes is also accompanied by significant changes in the number of farms. For example, among the commercial holdings on marginal lands, almost 4.6% of the traditional farms go out of business per annum and migrate to other destinations. In the bandwagon scenarios, income differences increase even further. These rather discouraging forecasts suggest policy interventions are needed to prevent an increasing gap between the incomes of households farming marginal and average lands. As already mentioned in the first section, policy interventions often imply the risk of locking too many farm-households into these fragile areas. When long-term prospects are limited, switching to alternative paths might become more difficult than without previous policy interventions. Again, the model helps to explore the dynamic effects of alternative policies and can thus inform policy formulation. In the Chilean case, potential path-dependencies could be found in the diffusion of innovations, but social hardships seem not to arise. For more details on the policy analysis and especially the role of land/water markets refer to BERGER (2000).

Finally, **Figure 5** illustrates the interplay of migration and innovation measured by the labor employed in agriculture. This regional indicator reflects all forms of migration – in and out, temporary and permanent – and is here compared with the labor capacity of all farm-households in 1997, the simulations' starting period. In the boundary scenario without technical change, approximately one third of the initial labor force is used off-farm and migrates to the non-agricultural sector permanently or temporarily. Ideal technical change, in contrast, attracts additional farm labor and converges to a higher equilibrium level of labor allocation in agriculture. Innovation is therefore an alternative to migration and has the potential of turning a sending region into a receiving region. But if the farm-households continue to depend on their communication networks in decision-making – the market solution with bandwagon –, then off-farm labor allocation only diminishes slightly over time, i.e. the effects of innovation and migration almost compensate. In this respect, the simulation results underline the importance of interpersonal communication and of cumulative causation in the process of innovation and migration.¹¹ Farm labor as an indicator for migration, however, does not capture the underlying structural change in the farm sector. As indicated in Figure 3, many traditional farms move out of the region, especially those in the group of commercial holdings. Growing farm holdings, especially in the middle size classes, absorb these lands, adopt new technologies and employ temporary farm workers. See BERGER (2000) for a more detailed discussion of these and other indicators of structural change especially those related to land and water markets.¹²

¹¹ Policy interventions that facilitate favorable conditions for technology adoption, especially investment and extension programs, and thereby encourage the employment of additional labor in agriculture are discussed in Berger (2000).

¹² Since empirical data were not available on how farm-households in the study region respond to rising opportunity costs, several model parameters are still based on *ad hoc* assumptions. A follow-up study will aim at clarifying these simulation results.

6. Conclusions

This paper presents an integrated simulation model that addresses the complex relationship between environmental stresses, migration and innovation. In line with the literature of new economics of migration, the model focuses on the decision making of rural households in developing countries who regularly make use of migration and innovation to cope with environmental hazards. It also considers the uncertainty-reducing effect of information becoming available when a few pioneering households start engaging in novel activities. Since migration and several crucial environmental processes in agriculture – such as evapotranspiration and flows of irrigation water – are spatial phenomena, the model integrates these biophysical processes in a spatially explicit way. By representing the farm-households' decision making and their local environment over time, the model forecasts land and water use changes that might emerge under different technological, political and environmental scenarios.

The model is encoded as a multiple-agent system, a relatively new concept of implementing complex computer models with the help of object-oriented programming languages. There is a one-to-one correspondence between real-world and modeled agents, that is, each single real world farm-household is represented by a single model agent. Several types of interactions among agents are endogenous to the model such as the contagion of information, exchange of land and water resources, and return-flows of irrigation water. A recursive whole-farm *mathematical programming* routine is used to mimic the decision making of farm-households. This one-to-one multi-agent representation facilitates examining the spatial context of agricultural production at a very fine resolution, as well as bilateral and direct interactions between agents. Including these direct interactions among agents broadens the scope of resource use modeling significantly because – apart from the frequency-dependent effects in migration and innovation – other economic phenomena such as the limited competition on land markets and upstream-downstream trade-offs in irrigation are now explicitly modeled.

To test its applicability, a model prototype is applied to the Melado River Catchment in Chile. Irrigation water is scarce and only sufficient for extensive cropping and livestock farming. An overall switch of production toward higher-value irrigation systems would first require the introduction of water-saving irrigation techniques and second the reallocation of water rights among farmers. Currently, many farm-households grow traditional crops with relatively inefficient irrigation techniques and locate some of their members in different areas and labor markets. Empirical studies have also found a high potential of outmigration among the traditional farm households.

By including networks of communication in the model, the simulation experiments indicate that interpersonal communication slows down the diffusion of innovations significantly and thereby accelerates outmigration. Far fewer farm-households remain in the farming business and adopt water-saving technologies than predicted by the standard modeling approach. One might therefore conclude that agricultural water use is locked into low efficiencies and that policy interventions to speed up the diffusion of water-saving innovations are called for. The paper reports some results of the policy analyses and illustrates the income effects on marginal lands as compared to the regional average. Under prevailing environmental conditions, innovation and migration seem to act as antagonists. Favorable conditions for technology adoption lead to increased employment in agriculture and might even turn a potential sending region into a receiving region.

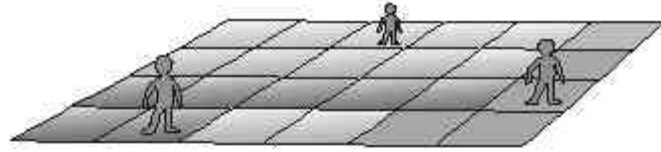
The pilot study demonstrates the usefulness of the multi-agent programming approach in incorporating the complexity of humans' responses to environmental changes. The approach integrates biophysical as well as socio-economic processes and captures the dynamic effects of complementary migration and innovation decisions. It makes allowance for potentially path-dependent adjustments; is capable of exploring the likely impacts of different technology and policy options; and generates useful information for policy analysis. Further testing of this model class and coupling with models of regional environmental change is called for.

References

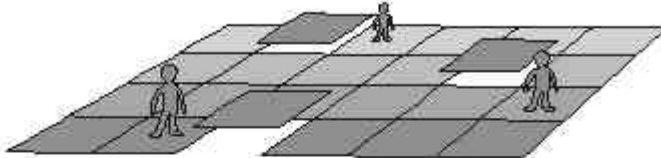
- BALMANN, A. (1997): Farm-based modelling of regional structural change: A cellular automata approach. In: *European Review of Agricultural Economics* 24, 85-108.
- BERGER, T. (2000): Agentenbasierte räumliche Simulationsmodelle in der Landwirtschaft. Anwendungsmöglichkeiten zur Bewertung von Diffusionsprozessen, Ressourcennutzung und Politikoptionen. *Agrarwirtschaft Special Issue* 186, Agrimedia.
- BERGER, T. (2001): Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. In: *Agricultural Economics* 25 (2/3), 245-260.
- BRANDES, W., RECKE, G., BERGER, T. (1997): *Produktions- und Umweltökonomik – traditionelle und moderne Konzepte*. Stuttgart.
- COCHRANE, W. W. (1979): *The Development of American Agriculture*. Michigan.
- COWAN, R., GUNBY, P. (1996): Sprayed to Death: Path dependence, Lock-In and Pest Control Strategies. In: *Economic Journal*, 106 (May 1996), 521-542.
- DIXIT, A.V., PINDYCK, R.S. (1994): *Investment Under Uncertainty*. Princeton, New Jersey.
- EPSTEIN, J.M., AXTELL, R. (1996): *Growing Artificial Societies. Social Science from the Bottom Up*. Washington.
- FAIST, T. (1997): The Crucial Meso-Level. In: HAMMAR, T. ET AL. (eds): *International Migration, Immobility and Development. Multidisciplinary Perspectives*. Berg, Oxford, 187-218.
- FISCHER, P.A., MARTIN, R., STRAUBHAAR, T. (1997): Should I Stay or Should I Go? In: HAMMAR, T. ET AL. (eds): *International Migration, Immobility and Development. Multidisciplinary Perspectives*. Berg, Oxford, 49-90.
- GILBERT, G.N., TROITZSCH, K.G. (1999): *Simulation for the Social Scientist*. Open University Press.
- HANF, C.-H. (1989): *Agricultural Sector Analysis by Linear Programming Models*. Wiss. Vauk, Kiel.
- HARRINGTON, J.L. (1995): *C++ and the Object-Oriented Paradigm. An IS Perspective*. New York.
- HAZELL, P.B.R., FAN, S. (2001): *Balancing Regional Development Priorities to Achieve Sustainable and Equitable Agricultural Growth*. In: Lee, D.R., Baret, C.B. (eds.): *Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment*. CABI Publishing, Wallingford, New York.
- HAZELL, P.B.R., NORTON, R.D. (1986): *Mathematical Programming for Economic Analysis in Agriculture*. New York.
- KLIOT, N. (2001): *Environment, Migration and Conflict: A Critical Review*. Paper presented at the Wengen 2001 Workshop.
- METCALFE, J. S. (1988): The Diffusion of Innovations: An Interpretative Survey. In: DOSI, G., ET AL. (Eds.): *Technical Change and Economic Theory*, 560-589.
- PARKER, D., BERGER, T. AND MANSON, S. (in print): *Agent-Based Models of Land Use / Land Cover Change*. Lucc Report Series No. 6. Lucc International Project Office, Louvain-la-Neuve.
- ROGERS, E. (1995): *Diffusion of Innovations*. 4. Ed., The Free Press, New York.
- STARK, O. (1991): *The Migration of Labor*. Basil Blackwell, Cambridge, Mass.
- STARK, O. (2001): *On the Economics of Migration: Beyond Wage Differentials*. ZEF Public Lecture on the occasion of receipt of the Humboldt Prize, Center for Development Research, Bonn, March 20, 2001.
- VALENTE, T.W. (1995): *Network Models of the Diffusion of Innovations*. New Jersey.

Figure 1: Spatial data representation and interdependencies

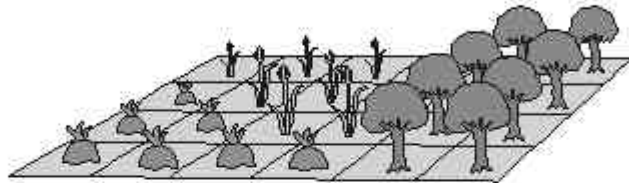
Layer 1
Human actor:
Communication
networks



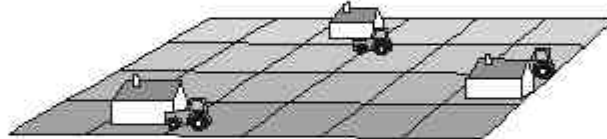
Layer 2
Land and
water market:



Layer 3
Landuse/
cover



Layer 4
Farmsteads



Layer 5
Ownership



Layer 6
Soil quality



Layer 7
Water flow



Figure 2: Frequency of water-saving irrigation techniques under different technological scenarios

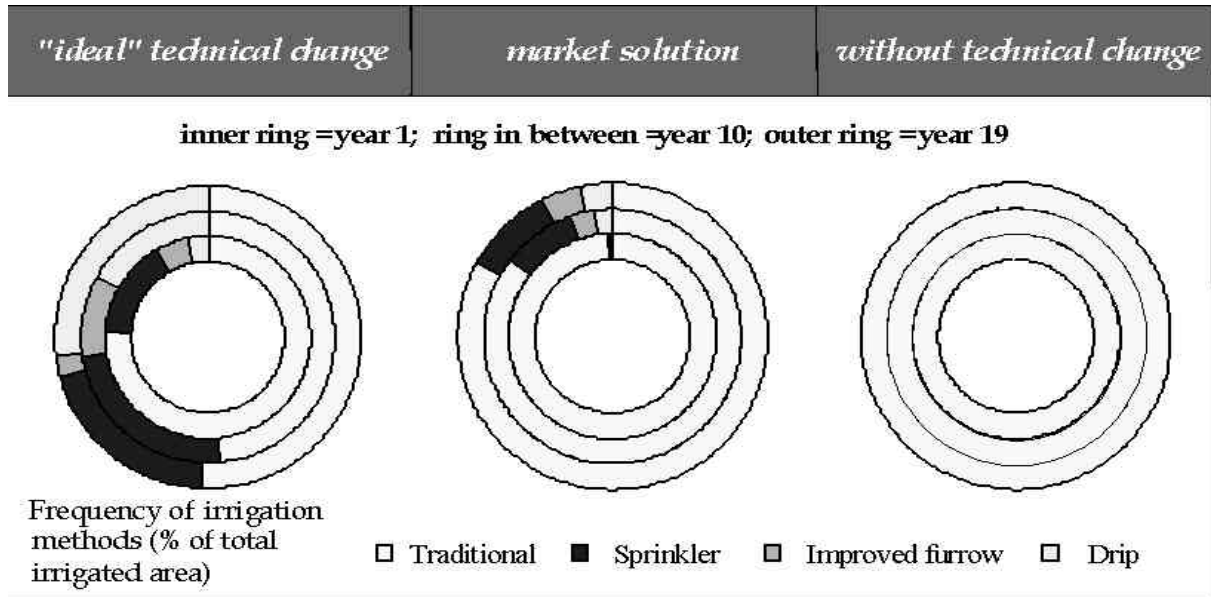


Figure 3: Average income and number of remaining traditional farm households

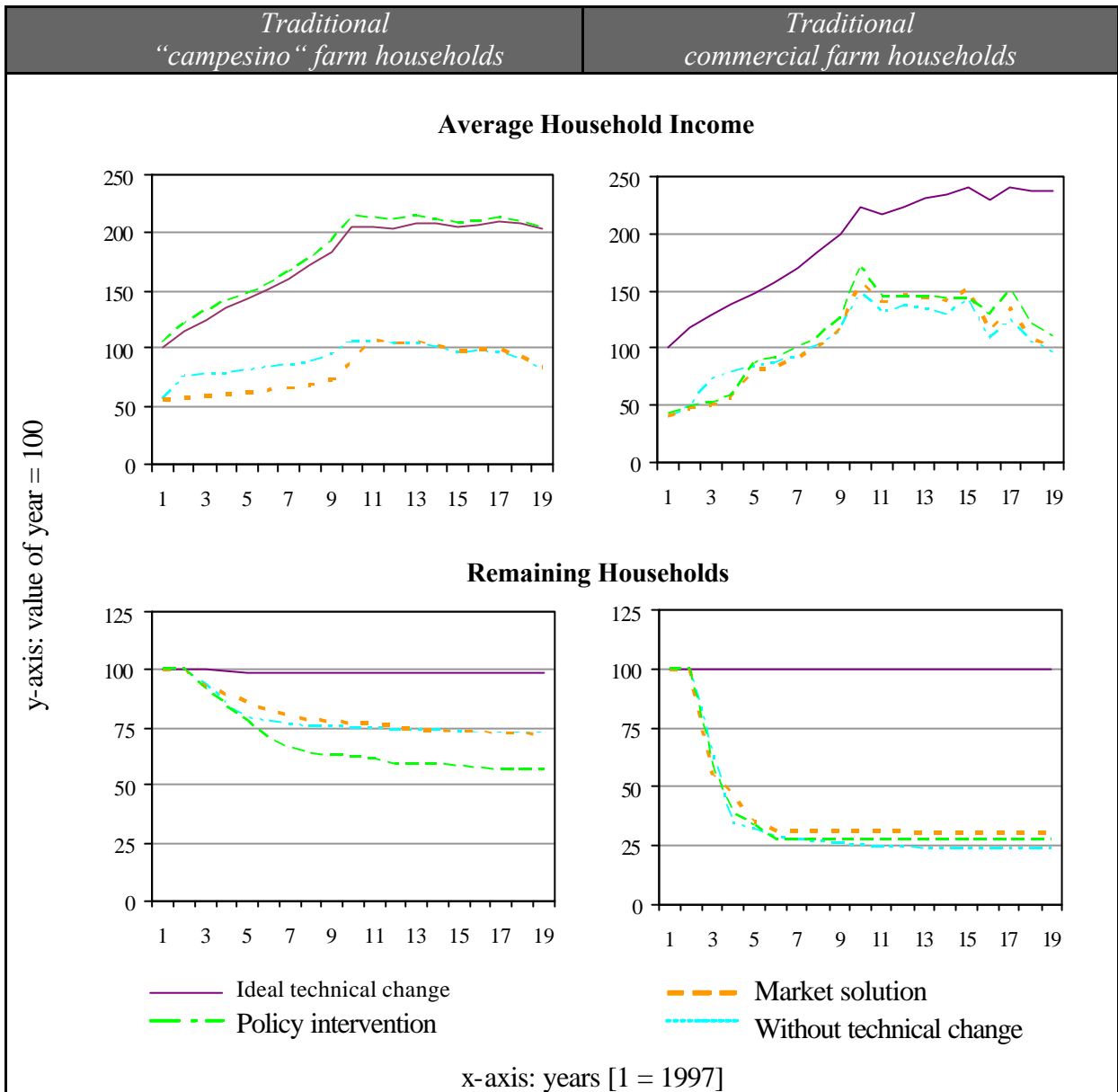


Figure 4: Relative income of farm-households depending on land quality (“ideal” technical change)

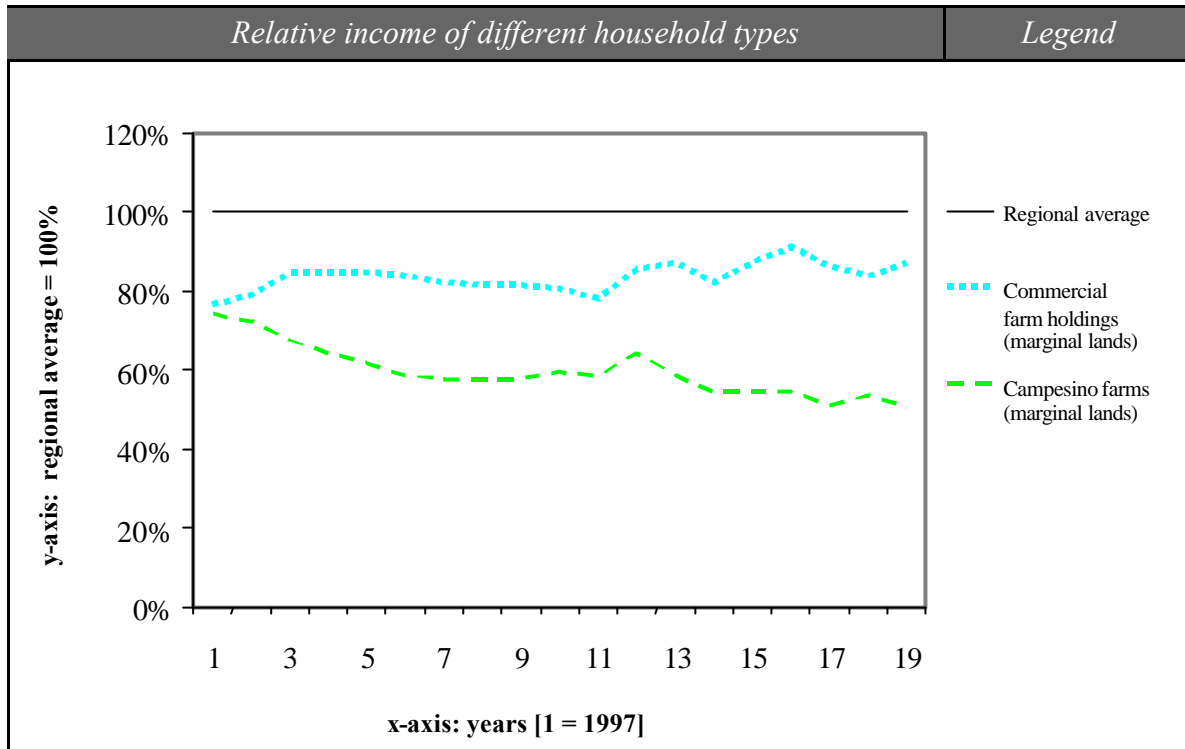


Figure 5: Farm Labor employed in the study region

