Trade-offs, efficiency gains and technical change – Modeling water management and land use within a multiple-agent framework

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Summary

Decisions on natural resource use are usually taken by individual resource users such as farm-households and landowners within an existing legal and policy framework; their consequences on the natural resource base, however, can sometimes be felt at much larger scales due to the complex interdependencies among these resources. Linking biophysical and socioeconomic processes, identifying their consequences at different scales or levels of analysis, and formulating suitable policy options based on these analyses remains a difficult research task. This article suggests to combine aggregate and disaggregate mathematical programming models that relate land and water resources within a multiple scale - multiple agent framework. Such an approach promises to generate valuable information for policy development as it captures more fully temporal and spatial scales of human-nature interactions; provides a way to address interrelated water and land use issues; and allows the inclusion of policy responses from farmers' and other resource users' points of view.

Key words: water and land use, integrated modeling, mathematical programming, multi-agent systems

JEL classifications: Optimization Techniques; Programming Models

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Tradeoffs, efficiency gains and technical change –
Modeling water management and land use within a multiple-agent framework[*]

1. Introduction

Avoiding, mitigating and – hopefully – solving conflicts over natural resource use requires first of all information and insights about the underlying biophysical and socioeconomic processes. Science-based information systems that take account of these processes could then assist in quantifying the tradeoffs, assess alternative allocation mechanisms, and inform policy development and analysis on interrelated land and water use options. Innovation in agriculture is a core element for improving water use efficiency and increasing food supply. Again, information systems might help detecting possible market failures in the technology diffusion and identifying institutional bottlenecks.

MCKINNEY et al. (1999) provide a comprehensive overview over modeling approaches applied to water resources management. They recommend the development of integrated economic-hydrologic models and outline some directions for future research. In the neighboring field of agricultural economics, multiple-agent models that represent farmers' decision-making processes and direct interactions have been used to analyze technical and structural change (BALMANN, 1997; BERGER, 2000). This paper discusses two exemplary model applications for both integrated economic-hydrologic river basin modeling (RINGLER, 2001) and multiple-agent modeling (BERGER, 2000) and suggests to combine these two approaches within a multiple scale – multiple agent framework. Such a widened approach promises to generate valuable information for policy development as it captures more fully temporal and spatial scales of human-nature interactions; provides a way to address interrelated water and land use issues; and allows the inclusion of policy responses from farmers' and other resource users' points of view.

2. Research questions revisited

Interrelated land-water modeling systems developed for policy analysis typically attempt to address some or all of the following questions:[1] (1) What is the optimal allocation of water and land resources taking into account existing physical, technical, and financial constraints? (2) What are the differences between actual and benefit-maximizing allocation and where can additional benefits be achieved most efficiently? (3) Which

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[1] Integrating land and water, which is essential for capturing the dynamics of interrelated biophysical systems (LAMBIN et al., 1999), is itself a complex task; the focus of the paper, however, is on the linkage of biophysical and socioeconomic processes.

constraints on land and water resources development are most binding? (4) How large are tradeoffs between competing water and land uses? (5) How do development paths under different environmental and technological scenarios look like? (6) What are feasible water and land management policies and what are their costs and likely effects?

Integrated economic-hydrologic models have been able to address some of these questions. ROSEGRANT et al. (2000) developed a comparative-static prototype model at the basin scale and applied it to the Maipo River Basin in Chile. The model captures upstream-downstream relationships in quantity as well as quality and optimizes water benefits across different water-using sectors. The model focus is on intersectoral water allocation among irrigation systems, urban areas, and hydropower production, and the benefits of tradable water rights as compared to other water allocation mechanisms.

Many challenges still remain for the integrated economic-hydrologic approach, in particular, regarding questions 4-6. Modeling the tradeoffs between interrelated water and land uses poses difficulties when the spatial and temporal interdependencies figure importantly. The water cycle, for example, is directly and indirectly influenced by land-use and land-cover change, and vice versa. Changes in land cover modify crucial hydrological processes such as evapotranspiration and groundwater recharge that in turn might restrict available land use options. Spatially explicit process-based hydrologic simulation models capture these feedbacks but are very data-intensive and difficult to link to economic models.

Another challenge relates to the comparative-static analysis that is usually employed. As has been discussed early on in the literature of agricultural sector models, optimal solutions derived from aggregate comparative-static model scenarios may in reality never be reached because of prohibitively high adjustment costs or “lock-in” (BRANDES, 1978). Quantifying these adjustment costs is complicated but would be required for dynamic model simulations in order to frame the corridor for plausible time paths. Closely linked to this argument, is question 6 on policy impacts. Identifying “optimal” resource use patterns from a viewpoint of policy may not be very useful unless ways are also found to induce the resource users to adopt these patterns. This could be achieved through the inclusion of appropriate positive objective functions (HAZELL and NORTON, 1986: 140). Incorporating more fully the resource users’ own objectives and constraints will certainly yield better forecasts of reactions to policy changes. In agriculture, for example, farmers’ heterogeneous financial and labor constraints, their perceptions, as well as communication networks do matter (BRANDES, 1989; ROGERS, 1995).

In which directions and by which means should, therefore, the scope of integrated modeling be increased? One suggestion might be to further extend the notion of system integration as outlined in MCKINNEY et al. (1999) by applying a multi-agent systems approach. This novel concept borrowed from the computer sciences could allow designing water and land use models not only as an abstraction of the real physical river basin that is affected by external socioeconomic shocks. Rather the models would include the socioeconomic system and endogenize its interrelatedness to the physical system; in other words, portray the river basin together with the resource users attached to it and capture the most relevant agent-agent and agent-environment relationships. The next section briefly introduces the concept of multi-agent systems and describes how it has been used in agricultural economics.

3. ‘Multi-Agent Systems’ and ‘Artificial Life’

Multi-Agent Systems (MAS) and Artificial Life (AL) are quite recent concepts originating in the computer sciences that have rapidly diffused to other disciplines as well and are now applied to the analysis of complex systems. Several competing definitions of MAS and AL can be found in the literature; we follow FRANKLIN and GRAESSER (1996) who define MAS as computer programs consisting of computational agents that sense their environment and act on it autonomously. They are constantly running processes and behave in a goal-oriented manner, i.e., they do not simply act in response to changes in the environment but so as to affect it purposefully over time. Two types of computational agents can be distinguished: software agents intended to help their human owners directly, and AL-agents that have indirect benefits. A good example for the first category is *Sumpy,* an MAS that fulfills the task of compressing and backing-up files in a UNIX file system and sleeps when the system is busy. Some MAS are also communicative and exchange information with each other or directly with humans such as PEA (personal electronic assistants) that synchronize their different owners’ time schedules and arrange meetings among them. In contrast to these software agents, AL-agents are designed to represent essential lifelike characteristics, for example, of humans, and are used in computer experiments for research into population dynamics. A prominent example is *Sugarscape,* an artificial society of multiple 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). Whereas these sugar-eating agents are rather simple-minded and may only serve as a very abstract representation of human decision makers, the concept of modeling real farm agents has a long history in agricultural economics.

In the early 1970s, RICHARD DAY described the agricultural sector as a complex system of farms and markets, in which feedback loops connect each economic agent with its own history of actions, its neighbors, and environment. Each agent pursues its own agenda and adapts to changing prices, revenues and quotas, which are exogenous from its point of view. The agents solve their decision problems autonomously while depending in their actions on one another through direct inter-agent relations and market feedbacks. DAY and SINGH (1975) were not able to encode this agent-based representation due to limited computational resources at that time and formulated a much less complex model of the farm sector instead. They neglected the spatial context completely, suppressed individual agent interactions, and represented all agents by one single model for the sector as a whole. The authors applied this model to an agricultural region in India to trace the economic impacts of the Green Revolution.[2]

Inexpensive, high-capacity computers, object-oriented programming languages, and conceptual advances in complexity theory make it now possible to overcome many of the technical and theoretical weaknesses of recursive farm sector models. The object-oriented programming language, in particular, provides a very efficacious and transparent way of organizing large amounts of economic data and to handle complex model dynamics. BALMANN (1997) developed a farm-based sector model and showed the theoretical effects the spatial distribution of farms has on the level of rent and the speed of structural change in agriculture. BERGER (2000) made allowance for heterogeneous farm agents and direct interactions between them. In place of a single objective function at the aggregate level, the MAS implementation of a farm sector model includes objective functions – such as income maximization or minimum subsistence levels – of all farm agents, their environmental feedbacks and carryover of individual resources.

Artificial Life is also an appropriate approach for capturing spatial phenomena in biophysical modeling, as several papers of a recent workshop on agent-based land-use modeling show (CSSIS, 2001). AL allows for the investigation of lower-level mechanisms that might lead to the development of higher-level structural and dynamical features in landscapes. Cellular modeling techniques, such as Cellular Automata (CA) and Markov Models have been applied to landscape modeling (BOCKSTAEL and IRWIN, 1999; PARKER ET AL., 2001). The basic units for modeling locally interacting "objects" are cells on a grid, whose transition rules include their previous state and the state of the neighboring cells. Advanced models use Geographical Information Systems (GIS) to store information about the state of cells in a landscape and feed this information back into the CA. The method of CA can also be used to represent the interactions of humanlike agents in physical or social space. Typically, the agents occupy positions on a two-dimensional grid of cells and the distances between them influence their interactions. BALMANN (1997) and BERGER (2000) employ a CA framework, which in the case of BERGER (2000) is directly linked to soil information and hydrology modeling (see section 5 below).

Although the agricultural sector models mentioned above differ in their computational form, they share one common feature. They are all based on the method of mathematical programming and employ it as a means of representing farmers' decision-making. Mathematical programming has also been combined with hydrologic and agronomic sub-models with the purpose of optimizing water allocation among different land and water-based uses. These coupled economic-hydrologic models are a subset of integrated river basin models as described in MCKINNEY et al. (1999). The following sections present two recent mathematical

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[2] DAY's work on recursive linear programming inspired numerous subsequent applications to agricultural sector modeling (MUELLER, 1979). Some of these – still aspatial – models were composed of several independent farm or group farm sub-models. In today's terminology one could certainly regard these multiple farm models as a simple

programming applications exemplary for an aggregate normative and a disaggregate positive approach to water and land use modeling. In the following, these two applications will be presented, including research questions addressed, model structure and implementation, and empirical results.

4. Example for an aggregate approach: The Mekong River Basin Model

The first example of a programming model applied to water resource issues presented here, is an aggregate water allocation model that has been developed for the analysis of water use patterns and allocation mechanisms at a transboundary and intersectoral level. Although the model is tailored to the prevailing conditions of the Mekong River basin, it can be adapted to other river basins (RINGLER, 2001).

Problem and research questions

Worldwide, there are only few effectively and efficiently operating international river basin organizations. Often, they do not succeed from the outset in reaching an agreement on the general principles and procedures for the cooperation in water allocation, or, reallocation of (water) resources remains cumbersome, even though agreement has been achieved in principle. A lack of perceived benefits from cooperation and a lack of understanding on water use patterns and on the tradeoffs among competing water uses contributes to the poor management of transboundary water resources.

Although the objective of the study was primarily a methodological one – to develop an integrated river basin model for analysis of water allocation and use; to test its ability to capture the complex interactions and tradeoffs among water supply and demands; and to assess intersectoral competition for water resources – the model also was to elucidate the role of appropriate institutions or water allocation rules at the basin level and provide insights of how to overcome some of the obstacles to effective management and transboundary water cooperation in the Mekong River Basin (research questions 1-4 in section 2).

Methodological pre-considerations

The research questions underlying model development – analyzing transboundary and intersectoral water allocation as well as testing alternative water allocation strategies at the basin scale – are reflected in the level of abstraction and complexity of the model structure. The river basin is chosen as the unit of analysis since basin-level analysis allows for: (1) comprehensive physical and technical management of water supplies; (2) integrated analysis of growing competition for water among agricultural, urban and industrial, and instream water uses; and, (3) based on this analysis, the development of water allocation strategies that are efficient, equitable, and environmentally sustainable (RINGLER, 2001).

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precursor of discrete multi-agent systems without connections between the subagents (FRANKLIN and GRAESSER, 1996).

The economic agents to be included in such a model are the basin-relevant off-stream and instream water users of all riparian countries. Modeling of large basins at this scale calls for aggregation in order to avoid excessive run time and other model complexities. Limited access to data in riparian countries and lack of data consistency across countries in addition to other research constraints are further determinants in the choice of aggregation. As a result, the spatial relationships between different water uses have to be captured in a rather coarse node-link network consisting of only the main source (rivers, reservoirs, groundwater aquifers) and demand nodes (irrigated crop fields, industrial and household consumption sites). Water flow is routed through the model system and hydrologic balances are calculated for each node in the network.[3] The model represents the economic system at a highly aggregated level with country/regional supply and demand of water, and clearly abstracts from agent heterogeneity or coordination failures. It computes the optimal allocation of water across water-using sectors on the basis of the economic value of water subject to a series of physical, system-control, and policy constraints.

Though aggregation facilitates practical model development it might overlook the potentially large variation in local conditions, including climate and water use patterns, and can thus result in more favorable model outcomes than actually exist in many local areas within the basin. Further disaggregation of the regional and country-level structure to the local/sub-regional level would be necessary to draw a more differentiated picture of the local/sub-regional water supply and demand situation.

System under study

The Mekong River is the dominant geo-hydrological structure in mainland Southeast Asia. The river has a total length of 4,800 km and the discharge averages 15,000 m^3/sec. The basin area covers 795,000 km^2 and is shared by six countries and about 65 million people. The Mekong River Commission is considered to be one of only few successful transboundary basin organizations worldwide. This success is reflected in more than 40 years of international cooperation for Mekong water resources — through periods of warfare and ideological confrontations — and culminated in the innovative "Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin" signed in 1995 among the four lower Mekong riparian countries. However, the 1995 Mekong Agreement is only a framework document that contains general principles and procedures for the cooperation in water allocation, but does not actually allocate water among the four member countries. Preparations for the negotiation of the "Rules for Water Utilization" began in earnest only in 2000 and the process of identifying rules that are acceptable to all the basin stakeholders will likely last several years.

Model implementation

The spatial and temporal resolution at which the model operates is rather coarse. The node-link network, which captures the spatial context of water uses along the Mekong River, includes the major river reaches

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[3] An alternative would be a cell-based model structure, e.g., when the model is directly linked to GIS coverages.

and nodes and several aggregate spatial units at the country level (except for those countries with geographically separate basin areas such as Thailand and Vietnam with two spatial units each, see **Figure 1**). A number of aggregate demand sites for the various water uses in the basin are connected to the seven spatial units in the river basin network. Aggregated agricultural demand sites are delineated according to the size of irrigated areas and administrative boundaries. Nodes for urban-industrial demand sites are connected to the basin network at the major urban centers. Reservoirs are aggregated for either power production or irrigation/urban-industrial water supplies. The basic flow balance at a node in the basin network is calculated as flow leaving the node equal to inflow into the node plus local drainage plus return flows minus withdrawals and (evaporation) losses.[4]

As no detailed hydrologic processes were simulated a monthly time step was considered appropriate for the hydrologic component. The crop-yield function in the agronomic/economic component is seasonal and the gap between the monthly water allocation and the seasonal crop yield function was bridged through a penalty function.[5] Instream uses can be modeled at different scales, depending on the detail and objective in question. Here, a monthly time step was used so as to obtain a uniform modeling time step. With respect to environmental and human-spatial interactions, physical constraints (e.g. flow routing through the system) and system-control constraints (e.g. reservoir operation parameters) ensure that the model's water allocation is not only optimal from an economic point of view but also feasible from a hydrologic and system-operation point of view.

The objective function of the mathematical programming problem maximizes the net profit or benefits from irrigation, municipal and industrial water uses, power production, wetlands, and fish production. The baseline scenario is the basin-optimizing solution, that is, the efficient water allocation an omniscient decision-maker seeking to maximize benefits across water uses and regions/countries would choose. In the real world, the transaction costs for such an allocation, which requires decision makers with 'perfect' knowledge about the basin water economy and the tradeoffs in intersectoral water allocation, are likely prohibitive. In addition, adequate mechanisms to compensate those countries that give up upon lower-valued water uses for the benefit of higher-valued uses in other countries and sectors are difficult to implement and seldom exist. Moreover, there are a series of other goals and objectives that influence decision-makers in their water allocation decision in the basin, which are not necessarily congruent with the objective of economic efficiency; for example, water allocation decisions reflecting the relative power structure in the

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[4] The spatial and temporal resolution represents a compromise between hydrologic and economic component requirements. Information exchange between hydrologic and economic model components can pose difficulties due to differences in modeling techniques, different spatial units of analysis, and varying time intervals and horizons (see also MCKINNEY et al., 1999).

[5] The penalty term minimizes the difference between the maximum and average crop stage deficit due to water stress for a given crop and demand site. Alternatively, the penalty term could have minimized the difference between monthly maximum crop evapotranspiration and monthly actual crop evapotranspiration across the crop-growing season.

basin or those based on customs and traditions. These issues are analyzed based on a series of alternative model scenarios.[6]

Main empirical results

In the following, selected empirical results are presented that relate directly to the research questions in section 2. During the dry season and in low-flow years, tradeoffs between off-stream and instream water uses are evident. Tradeoffs are particularly strong between fisheries and other water-using sectors, in particular, irrigation, urban-industrial water uses, and hydropower production. There is also a significant tradeoff between saltwater intrusion and profits from irrigation, but the tradeoff only plays out at high levels of water abstractions, or at substantial increases in downstream flow requirements.

As basin water demands cannot be fully met – even in the baseline year of 1990 with considerably less population than today – the Mekong River Basin has basically reached a semi-closed state. While water resources are fully committed to productive off-stream and instream uses during the dry season, excess water is still available during the wet season. An alternative scenario analyzes the impacts of planned mainstream hydropower development on the basin economy. Whereas hydropower and irrigation are typically complementary uses as additional dry-season flows can be used for expanding irrigation, the decline in wet-season flows could have large adverse impacts on the ecology of the largest inland lake in Southeast Asia, Cambodia’s Tonle Sap, which directly depends for its productivity on the size and length of the wet-season flooding period.

The model results also show that a change in the cropping pattern and the choice of crop alone could save large amounts of water resources in the dry season, as both, the irrigation water applied and the water productivity vary substantially by crop. Moreover, crops with a low productivity of water tend to be the least profitable crops.

Water allocation mechanisms need to be efficient, equitable, and environmentally sustainable. The model developed for the Mekong River Basin inherently ensures efficient water allocation in the basin as water is allocated according to its scarcity value to the highest valued uses and, once those are satisfied, to other uses, so long as the overall economic profit from water use across the basin increases. An analysis of alternative water allocation mechanisms that explores the impact of parity in allocation on basin profits shows that to achieve both equitable and optimal benefits from water use across countries and sectors, the strategy should be to strive for the largest basin water use benefits and then to redistribute these benefits instead of the water

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[6] The model has been coded in the GAMS modeling language, a high-level modeling system for mathematical programming problems. It consists of 4,476 single equations (rows) and 9,675 single variables (columns) with 16,721 non-zero coefficients. The model was calibrated to 1990 data and close to replicates actual water use pattern by inclusion of physical, system-control, and policy constraints. The model results were compared to results of partial studies for basin areas as feasible, for example for the value of water by crop in the Central Highlands of Vietnam. A

resource. However, there are only few functioning examples of transboundary compensation mechanisms in international river basins, thus the feasibility of such a policy option remains questionable (for more details, see RINGLER, 2001).

5. Example for a disaggregate approach: The Melado River System Model

The second example, a highly disaggregated economic-hydrologic model, deals with different research questions than the Mekong River Basin model. It concentrates on intra-sectoral water and land allocation in agriculture and attempts to provide answers especially concerning future technological and structural change (BERGER, 2000).

Problem and research questions

Agricultural intensification and, in particular, higher levels of efficiency in water and land use are key elements for improving food security in developing countries. Both generally require some form of innovation, e.g. farm investments in superior land-use practices and irrigation methods, agricultural extension, and, of course, institutional change. Several authors have argued that viewing land- and water-use improvements as exogenous technical change can lead to misleading policy recommendations and certainly to an under-emphasis of farm investments as a policy issue. In line with this argument, the model here focuses on the diffusion of water-saving irrigation methods in a watershed; the effects of innovation on farm structure; and the impacts of possible government interventions aiming at supporting farmers to improve their resource use efficiency.

Methodological pre-considerations

Though currently only a prototype, the model is in principle designed for providing policy-relevant information, especially regarding policy impacts on different farm and resource user groups. By means of computer simulations, it should facilitate exploring suitable policy options and forecasting likely land and water use changes as the result of technical and structural change in agriculture. 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, land and water rental markets, markets for land and water user rights, change in farm sizes – require the modeling of heterogeneous farm-households and inter-household linkages. The spatial context figures importantly – e.g. upstream-downstream water uses, local water and land markets – so that spatial relationships have to be included as well.

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series of sensitivity analyses was carried out to test the model's robustness and to compare model behavior to the results of other models. See RINGLER (2001) for details on the model's verification and validation.

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 km^2 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 first require the introduction of water- saving irrigation techniques and second the reallocation of water rights among farmers – intersectoral water transfers are at present not relevant in this mainly rural area. Currently, many farmers grow traditional crops such as cereals with relatively inefficient irrigation techniques and make accordingly only limited use of water trade. The situation might, however, change rapidly in the coming 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.

The temporal period being modeled is 19 years – starting in 1997 – in order to capture the complete process of sectoral adjustment in agriculture. To model the adjustment process at the farm-level, very disaggregated land use types in agriculture and forestry are being included: 5 soil types, 3 technological levels, 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 solely concentrates on surface water flows in agriculture. The model only includes those farm-households and non-farm landowners who engage in land and water markets and whose plots belong to 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 level. Other real world agents – such as farm workers and *minifundistas* with farmland below 2.5 ha – are not included in the analysis 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 determined 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. Based on intensive empirical analysis, both holding types were found to represent two distinct social networks. Within these networks, communication takes place, and five subgroups corresponding to different adopter categories – innovators, early adopters, laggards, etc.– are distinguished.

In accordance with theoretical considerations and findings from in-depth interviews, all model agents seek to maximize expected incomes without exhausting their land and water assets, i.e. they are assumed to have a preference for staying in the farm sector and may accept family incomes below opportunity costs. As a special case, the agents may also behave consistent with standard economic theory, that is, have perfect foresight with respect to farm prices and leave the farm business whenever their opportunity costs are higher.[7] The agent's individual decision making is implemented by means of recursive whole-farm mathematical programming. Each farm agent has its own "positive" objective function, resource constraints and updates its expectations for prices and water availability. A mixed-integer linear programming routine is used for farm investment and land rental decisions. In this respect, the model has similar characteristics as 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) one single model agent represents exactly one single real world farm-household and there are as many model agents as farm-households located in the region under study; and (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 multi-agent systems representation facilitates considering 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 mathematical programming significantly because several economic phenomena that standard approaches cannot easily address are now explicitly modeled. Firstly, the theoretically well-known effect that internal transport costs have on the level of rent by limiting competition on the land market is directly considered.[8] Here, the model captures the agents' location and internal transport costs through a raster-based geographical information system and incorporates local land markets with endogenous price formation. Secondly, it reflects frequency-dependent effects that in reality may drive the dynamics of technical change and lead to a "treadmill" situation in agriculture, as COCHRANE (1979) named it. When farmers differ in their innovative capacity and only the "early birds" are initially able to adopt a cost-saving technology, the "laggards" wait and learn from the early birds' experience until they can successfully imitate. Because of their lower adoption costs, the innovative farmers enjoy quasi-rents and may then absorb the land resources of the laggards. The model implements this

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[7] 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.

[8] Internal transport costs from the farmstead to a plot shape a kind of "von Thünen ring" around each plot that is offered on the land market. As a consequence, only few neighboring farms compete for a specific plot; however, land prices might rise sharply when several farms with high marginal productivity attempt to expand their acreage.

type of imitation process in social networks with the help of adoption constraints and network-thresholds.[9] Again, the model allows to consider the standard concept of perfect land markets and equilibrium diffusion processes without different adopter categories as special cases.

In its Chilean version, the model accounts for hydrologic-agronomic relationships only in the form of runoff and soil-type specific crop-water production functions.[10] Feedbacks are included in the model as monthly irrigation return flows that affect downstream water availability and may force farmers to undersupply their crops temporarily or even to abandon them completely.

As already mentioned above, the model employs a cell-based data representation where 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. Mainly neighboring model agents compete for each offered plot that the agent with the highest bid eventually obtains, provided that his bid is higher than the asking price. The spatial interactions of the water resources system, on the other hand, are represented at a much coarser scale because grid cells are grouped to hydrologic units of an average size of about 32 km^2. The model reflects either perfect water allocation – 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. **Figure 2** 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 of spatial nature (return flows, land and water markets) and of social nature (communication networks). Land cover/ use and water supply of a particular grid cell results from the decision-making process at the farm level where technical, financial, and higher-level social constraints are reflected.[11]

Main empirical results

This disaggregate, intra-sectoral model addresses particularly questions 5 and 6 of the list in the second section. By representing the resource users' own decision-making in a spatially explicit way, it analyzes competing land and water uses over time and investigates the role of technical change in agriculture. Two main results, which demonstrate the type of information the model generates, will be discussed briefly.[12]

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[9] See BERGER (2001) for more details on the implementation of Cochrane's treadmill by means of empirically estimated network-thresholds.

[10] The model will be soon extended to account for nutrient flows and erosion, see BERGER and WOELCKE (2001).

[11] A multiple-agent programming environment was developed, drawing on BALMANN's (1995) cellular automata source code. The 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.

[12] The model is a positive model and therefore replicates reality. Having calibrated the model to a base year, standard validation tests for mathematical programming were performed. Since the model has many degrees of freedom and

Figure 3 shows how land-use patterns might change over time under different technological and market scenarios. The middle graph depicts the evolution of land use under “ideal” conditions when the model’s farmers adjust ‘smoothly’ to technical change as predicted in the standard economic approaches. The Mercosur agreement implies increasing prices especially for fruit and horticultural products and decreasing prices for cereals. Within only a few years, cereals almost disappear whereas fruit plantations and horticulture expand their acreages considerably. A comparison with the graph on the left side reveals what might be called the ”pure price effect.” Here, land use is shown under ideal technical conditions with constant prices. Only minor land use changes take place over time, e.g. forest is slightly reduced and fruit plantation increased. The “pure innovation effect” can be isolated in comparison with the right-hand graph showing the land use change within the Mercosur but without any technical change. This scenario reflects a hypothetical situation, where farmers are reluctant to innovate and refuse any technology adoption. Accordingly, the acreages of the highly profitable fruit and horticultural innovations do not extend. The model farmers only exchange cereals for legumes, which will face increasing prices within the Mercosur. The ideal and the conservative scenario can be interpreted as extreme cases; reality will probably lie somewhere between these two boundaries.[13]

Figure 4 displays agricultural water use over time by comparing the frequency of several irrigation methods with different on-field efficiencies. Again the right- and left-hand graphs reflect the extreme scenarios of ideal and without any technical change. 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. The graph located in the middle, in contrast, shows the expansion of modern irrigation techniques under “bandwagon” conditions, that is, when the model’s farmers have to learn from their neighbors’ experience and behave like in Cochrane’s treadmill model. The diffusion of water-saving innovations is then significantly slowed down and reaches only a sixth of the irrigated area over twenty years.

One may therefore conclude that market-driven innovation takes considerable more time than predicted by the standard equilibrium concept and could then ask for special resource management policies 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. This program includes special credit schemes to facilitate the adoption of water-saving innovations, public investments in

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contains highly recursive dynamics, extensive robustness experiments and statistical tests were conducted. Finally, comparisons of performance with other models helped to create certain trust in the model’s behavior and results. More details on verification and validation are given in BERGER (2000).

[13] The “ideal” scenario corresponds to the “equilibrium diffusion concept” that assumes *a priori* complete information sets. Differences in time of adoption are explained by indivisibilities and minimum farm sizes. ROGERS (1995), in contrast, cites much empirical evidence supporting the “disequilibrium diffusion concept.” Farmers apparently rely at the most critical stages in their adoption decision process on information brought to them by peers, that is, information sets are incomplete. See BERGER (2001) for more details.

irrigation facilities as well as fertilizer subsidies, among others. The model helped to explore the likely effects of these policy changes on economic and biophysical indicators along alternative development paths. More details on the policy analysis and especially land/water markets can be found in BERGER (2000).

6. Integrating both approaches: multiple agents on multiple scales

This section compares the Mekong and Melado models and argues that integrating both programming approaches into a multi-level multi-agent framework has several conceptual and computational advantages. It discusses possible forms of integration and closes with some ideas for implementation.

Clearly, the differences in model specification stem from different research questions put to the Mekong and the Melado models. In the Mekong case, the problem of transboundary and intersectoral water allocation is addressed. Since the basin under study has a vast spatial extent and only few micro-level data are available, a high level of abstraction and aggregation is chosen. As discussed above, aggregation facilitates practical model development, but implies an unavoidable aggregation bias of unknown order. The Melado case, on the contrary, deals with intra-sectoral water allocation in a relatively small river catchment. The model focuses on phenomena, such as technology diffusion and local water/land markets where individual inter-agent linkages figure importantly, and analyzes the policy impacts on different farm types. Accordingly, a very low level of abstraction and aggregation is chosen. The model is free of aggregation bias, but subject to sampling bias.[14]

Though working on different spatio-temporal scales, a comparison of the constituent elements reveals a high degree of similarity between both models. They employ a similar mathematical representation of the physical water resources system as well as of production functions and technology sets. Their structural representation of economic motives and decisions builds on the same basic concept of human decision-making and market environments. In both models, water allocation is the result of agents' decisions that are mimicked by solving a mathematical programming problem. The main difference is, of course, that in the Melado case one model agent represents one real farm-household, whereas in the Mekong case one model agent represents the aggregate of all water resource users in the basin. The Mekong model could therefore be considered a multi-agent system with one "super-agent." These similarities suggest that both models could be integrated into one multilevel multi-agent modeling system.

What can be gained by integration of both approaches? Why not continue to use separate models at different scales, each tailored to a specific research question? Several conceptual and technical reasons clearly favor the integration into a multilevel multi-agent framework: (1) This kind of framework could provide a better

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[14] See HANF (1989: 20) for a discussion of aggregation vs. sampling error. Although the Melado model represents all real farm-households in the catchment under study, the farm-level data set relies on a farm-household sample that was "blown-up" by a recursive data generator (BERGER, 2000).

representation of interrelated socioeconomic and biophysical processes occurring at different spatial and temporal scales (HOLLAND, 1998). As has been demonstrated in the Melado case, a spatially explicit multi-agent programming model may capture important interactions across time and space among heterogeneous agents (diffusion of innovations) as well as between agents and their environment (downstream irrigation water). By the same token, PARROTT and KOK (2000) point to the usefulness of AL techniques for incorporating complexity in ecosystem modeling in general. By incorporating a high degree of social and spatial heterogeneity multi-agent systems could also represent "nested hierarchies" and phenomena emerging across different scales. As PARKER et al. (2001) argue, nestings imply that an individual agent or parcel is likely influenced by, and in turn influences, processes operating at multiple spatial scales. In the case of human agents, for example, family members interact to form a household, which may then interact with other households of the same village so that finally institutional changes at the community level occur, which in turn set new constraints for the resource use of each family member.

(2) A multiple-agent framework allows a direct and complete representation of the resource management problem being analyzed. Individual resource users such as farm-households and landowners take decisions on natural resource use within an existing legal and policy framework. A natural resource planner cannot dictate certain resource use patterns; rather he has to identify suitable policy incentives that motivate resource users to cooperate. HAZELL and NORTON (1986: 140) present the formal conceptual model an agricultural policy-maker faces. The policy problem of finding an "optimal" cropping pattern in terms of specified policy goals can be decomposed into two levels or scales: the macro (policy) problem – which policy instruments to apply given predictions of how the farmers will react – and the micro problem of predicting the farmers' reactions taking into account that they adjust to these policy changes under their (i.e. the farmers') constraints pursuing their own interests. HAZELL and NORTON (1986: 320) discuss several multilevel procedures and advocate a two-level method of micro- and macro modeling so as to explore the "policy feasible space." A multi-agent systems specification would allow to conduct this kind of multi-level policy analysis for the case of natural resource management.

(3) Biophysical simulation models are usually calibrated at the micro-level whereas economic models operate at a rather aggregate level. Aggregating the biophysical data so as to link it to an economic model implies a considerable loss of statistical information. An integrated multi-agent system can, in principle, be structured so as to perfectly match the scale and structure of available data. This is a very interesting aspect because data disaggregation procedures are currently being developed that will help to infer micro behavior from aggregate data consistently (HOWITT and REYNAUD, 2001). Socioeconomic and biophysical data collections at multiple spatial and temporal scales might then be generated and fed into a multiple-agent programming model.

(4) Equipped with inexpensive computers and object-oriented programming languages, empirically grounded programming models can now be implemented that were considered infeasible a decade ago. HANF (1989) estimates in his state-of-the-art review that about 20,000 farm models with a model size of 100 * 100 can represent the farm sector of the European Community. An independent farm-programming model of this size, implemented as a discrete multi-agent system, could easily be run on a desktop computer of 1999. If *Moore's Law* – that computing power doubles every 18 months – continues to apply for a few more years, we might be able to run a discrete farm multi-agent model even for the extended European Union as a whole.[15] The object-oriented programming language provides a very efficacious and transparent way of organizing large amounts of data and to handle complex model dynamics. By implementing agents as objects, the computational model can be encoded in a clear modular form. As HARRINGTON (1995) shows with the instructive example of a simple program for calculating debt servicing, an object-oriented implementation considerably increases the extendibility and portability of previous verified source code. The code of BERGER's (2000) multi-agent model might, therefore, be extended relatively comfortably by, for example, ecological constraints or interfaces with GIS-applications.

The next question to be raised in this context is how to implement a multi-level MAS and apply it to the issue of water and land use. Several forms of integration from loose to tight are possible:

(1) The loosest form of integration is to run an aggregate and a disaggregate multiple-agent model separately. Taking the aggregate optimization outcome as the basin-optimizing solution, one could then compare the disaggregate model results against this "benchmark" scenario. Different solutions indicate likely directions for policy response and provide a first estimate for time length and costs of adjustment (BERGER, in preparation).

(2) A tighter form of integration is deriving input data for the aggregate model from fine-scale simulation experiments, similar to the two-level approach described in HAZELL and NORTON (1986: 321). Disaggregate sub-models focusing on ecological 'hot spots' would then inform the larger-scale, aggregate models. This kind of integration could support low-cost – that is model development and run cost – representation of biophysical processes without losing the economic optimization approach. Alternative forms of meta-modeling techniques such as used in Ruben and van Ruijven (2001) are also possible.

(3) A third option is to implement a multiple-agent programming model where different types of agents interact. Some model agents represent single actors (e.g. a large-scale farm), other agents represent groups of

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[15] We do not argue here that larger models are necessarily better models and that one should implement an EU farm sector model as a discrete multi-agent system. This calculation is only meant to illustrate the enormous technical potential recent advances in information technology facilitate. Our estimate uses some rough figures taken from BERGER's (2000) multi-agent model that was run on a Windows NT desktop computer of the year 1999 with 450 MHz. One farm agent requires about 7,400 Kbytes RAM (including the hydrological model) and less than 20 sec. CPU time for solving about 220 LP problems of 120 * 240 over a 20 years horizon.

actors (a multitude of small-scale holdings), or entire sectors (non-agricultural resource owners). This is not a new idea; conventional recursive programming models with intra-sectoral linkages might implement this kind of feature as well. However, a multi-agent framework would be recommendable for encoding this type of approach as an integrated economic-hydrologic model supported by GIS. Heterogeneity in form of carryover of resources and spatial data storage could be handled very effectively. Using an object-oriented programming language would, therefore, significantly reduce model development costs and numerical difficulties.

(4) The closest form of integration would be to represent nested hierarchies as well as upward and downward linkages within a more fully connected multi-agent system. Emerging social norms, land allocation to immigrants, and common pool resources management, in general, are examples where micro-level phenomena influence macro-level outcomes that in turn affect units at the micro scale. Experiences with empirically parameterized models are to our knowledge yet not available; several research teams, however, are currently working in this direction (BOUSQUET et al., 2001).

7. Conclusions

This article focuses on the challenges that exist in representing interrelated socioeconomic and biophysical processes at multiple scales and in incorporating complexity in natural resource use modeling. One suggestion to address these challenges might be to further broaden the notion of system integration that underlies current integrated modeling approaches. An extended representational model of interrelated water and land use would portray the physical river basin together with the resource users attached to it and capture the most relevant agent-agent and agent-environment relationships. Multi-agent systems and Artificial Life are recent concepts originated in the computer sciences that appear highly suitable to encode this representational model in computational form. Moreover, they have early precursors in farm sector modeling and can thus build on a large body of experience in agricultural economics.

The method of mathematical programming is one promising candidate to implement the human behavior component in multi-agent systems as a representation of river basins, their resource users, and human-nature interactions. The paper reviews two recent mathematical programming models applied to water and land use issues at an aggregate and disaggregate level of analysis, respectively. It discusses briefly how the specific research questions motivated the choice of model specification. Some exemplary simulation results are presented to illustrate the type of policy-relevant information that can be generated with these integrated modeling systems.

Based on a comparison of the structural and mathematical representation in both model specifications, the article suggests to combine aggregate and disaggregate mathematical programming of interrelated water and land use. Several conceptual and computational reasons clearly favor the integration into a multiple scale -

multiple agent framework, such as a better representation of the scale and structure of available data; a reduction of model development costs and run time through the combination of selected micro-level detail within a more aggregate, larger-scale framework; and the ability to account for micro-macro and macro-micro feedback effects.

Of course, mentioning only the theoretical benefits of applying a multiple-agent approach conveys an incomplete picture. The ultimate question is whether the potential benefits from increased understanding and superior policy advice more than balance the additional costs of introducing more complexity into the modeling effort. Critics might also argue that the ambiguous experience of adaptive programming models in agricultural policy does not bode well for this research work and that minor modifications of the standard neoclassical model might capture the same richness without the messiness of a highly complex, numerical simulation approach.

Our answer to this skepticism builds on two arguments. First, the cost structure has completely changed during the last years. Computer memory and processing constraints are much less binding compared to 20 years ago, object-oriented programming languages facilitate a much faster model development, and disaggregate, spatially explicit data sets have become more widely available – thanks to remote sensing techniques, recent advances in econometrics, and the internet. Second, we advocate the application of the multiple–agent approach to those research questions where conventional economic models are inapplicable or difficult to use, namely for analyzing the spatially disaggregate consequences of environmental conflicts, market reforms, and technical change, especially in developing countries. We see multi-agent systems as a complement to existing well-established economic approaches. They amplify the range of economic methodology by introducing more “economic thinking” into biophysically-inferred river basin and land use modeling.

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Figure 1: The Mekong River Basin Node-Link Network

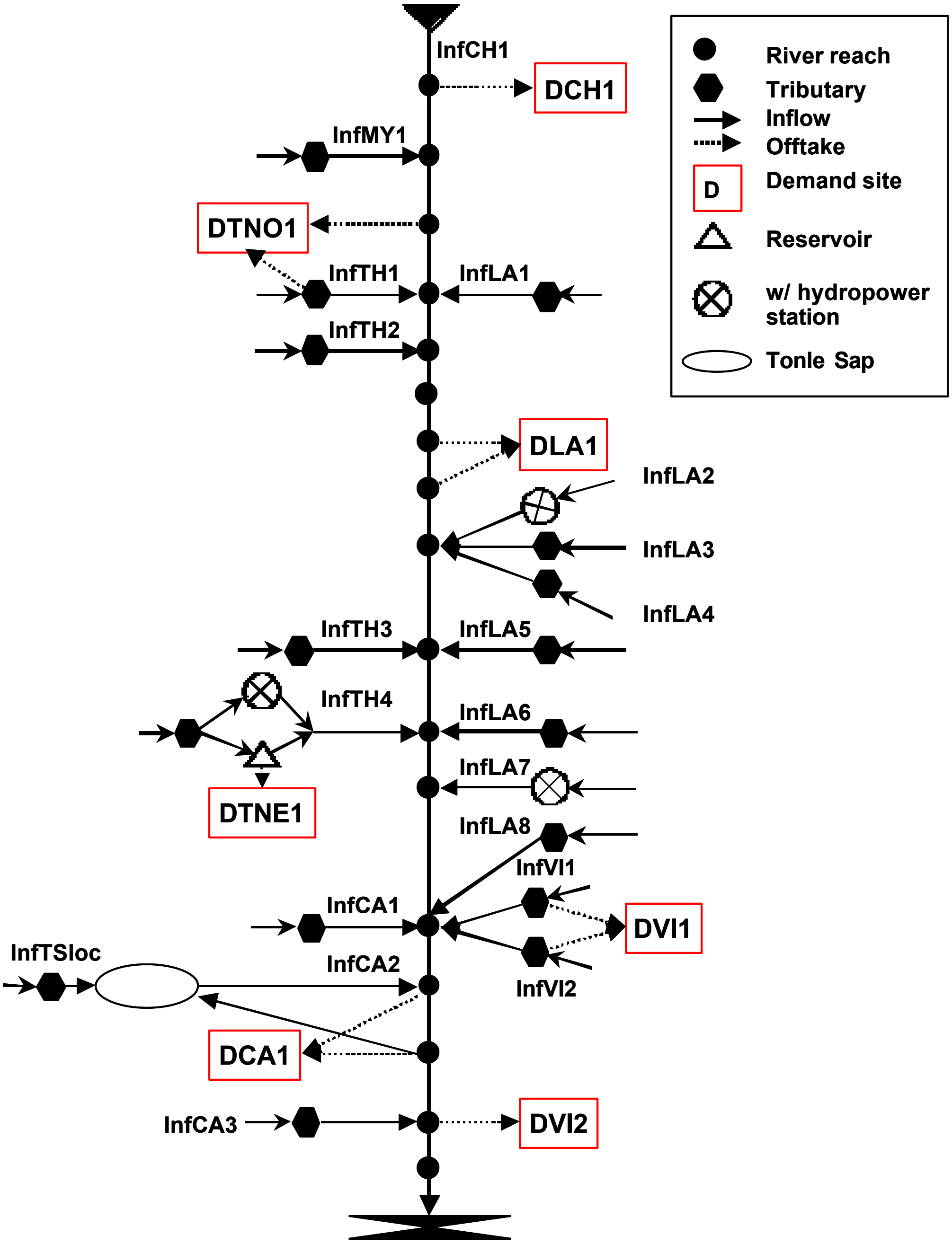

Figure 2: **Spatial data representation and interdependencies**

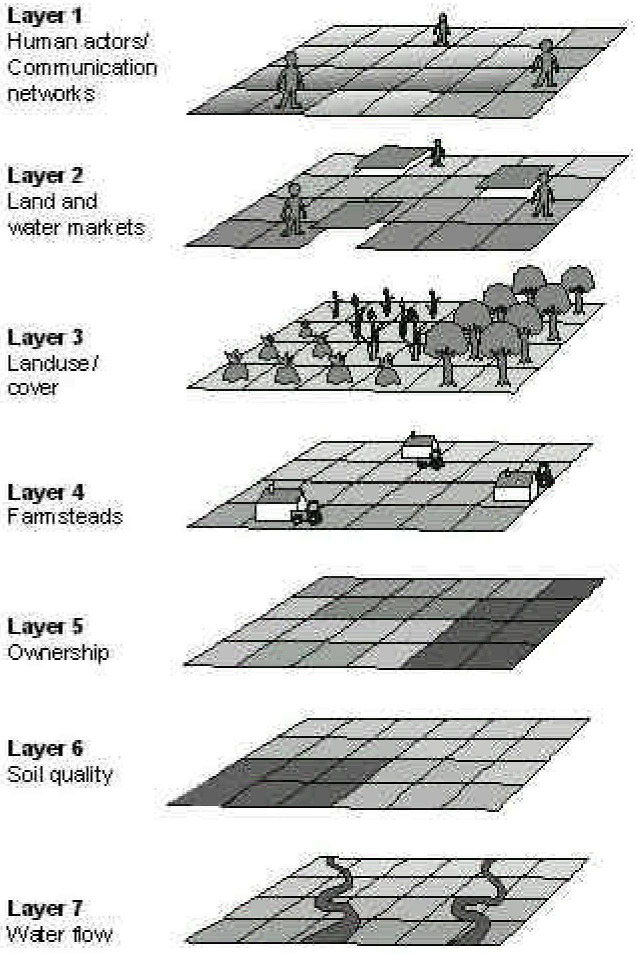

Figure 3: Land-use change under different technological and market scenarios

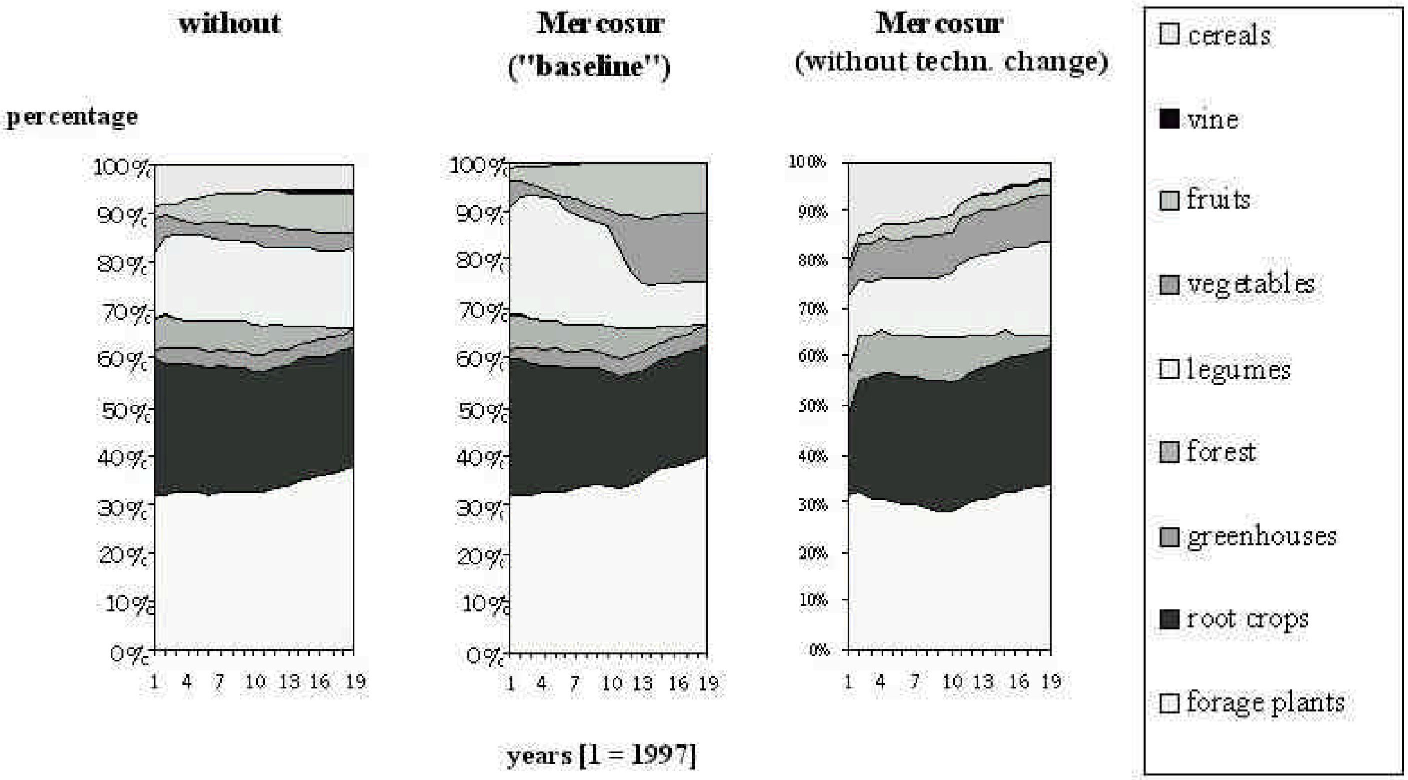

Figure 4: **Frequency of water-saving irrigation techniques under different technological scenarios**