Modelling Self-Organization Processes in Socio- Economic and Ecological Systems for Supporting the Adaptive Management of Forests

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Abstract: Managing the numerous and interrelated processes between man and nature in order to use renewable resources in a sustainable way is confronted with conflicting objectives, external effects, complex interdependencies, uncertainty and other features that make it nearly impossible to come to unambiguous optimal decisions. Self-organization in socio-economic and ecological systems - the process of structuring a system by the elements of the system themselves without hierarchical or external control - is often the reason for ambiguity and uncertainty. Adaptive management is an approach to deal with these challenges. This natural resource management method is permanently monitoring both socio-economic and ecological systems in order to be able to react rapidly on any development pushing the systems into an undesired direction. Understanding and simulating the underlying self-organization processes helps to make the adaptive management of renewable resources both more effective and more efficient. In this paper we present a simple conceptual model of self-organization in socio-economic and ecological systems to understand better their effects on the interrelations between them, applied to the special case of forestry.

Keywords: self-organization; agent-based modelling; forest succession model

1. INTRODUCTION

The paper is related to the on-going discussion on sustainable use of renewable resources. This is a complex problem that encompasses socio-economic as well as ecosystem processes. It is characterized by complexity, a high degree of uncertainty, and information deficits and asymmetries [Holling, 1978]. Self-organizing processes in the biosphere and anthroposphere restrict, often even eliminate the possibility for prediction and control and are a major reason for the difficulties that arise in managing natural resources. For the effective management of renewable resources it is necessary to design a more flexible, feedback-driven, and continually adaptive management process [Grumbine, 1994; Holling, 1978] and to broaden the scope by including socio-economic processes in addition to those in ecosystems [McLain and Lee, 1996; Holling, 1978; Peterson et al., 1997; Haney and Power, 1996]. We want to contribute to this so-called 'adaptive management' model by gaining an in-depth understanding of self-organization processes in socio-economic and ecological systems. Self-organization processes extracted from agent-based models provide additional information to field surveys and expert knowledge to identify the key parameters and processes underlying the dynamic behaviour of the system. To find this key parameters and processes is very important, because explicitly monitoring them can help to recognize ongoing changes earlier and adapt the management in time accordingly.

We present a preliminary, still very simple version of a self-organization model concerning the use of forest resources. The total model consists of two separate models, one for socio-economic, the other for ecological self-organization, which are interlinked. The paper presents a work in progress, therefore the final chapter will give an outlook of how the model could be further developed.

2. SOCIO-ECONOMIC SUBSYSTEM

In this chapter we describe the agents included in the socio-economic model and give an overview of the interrelations between these agents.

2.1 Agents: forestry and timber industries

The agents in the socio-economic model belong to three major categories: forestry, communities and timber demanding industries. Other potentially important agents like tourism or hunting are not included in the basic model, while agents like policy, demand for timber products and competing sources of timber supply are considered as exogenous forces.

In general, any socio-economic agent, be it an individual person or an organization, is defined by a strategy (S) and a set of production factors (F). In our model there are only agents with a single strategy. A strategy consists of an objective (Z) and a set of routines (R), comprising:

- Expectation models (E) concerning the effects of actions on and the behaviour of the agent's environment with specific timeframes.
- Action rules (A) employing available production factors.
- Evaluation standards (V) comparing the achieved results with the stated targets.
- Update rules (U) regarding when and which objectives have to be adjusted and new routines have to be applied in case of unsatisfactory results of V.

Agents evolve by changing their strategies. In our model an agent can adjust his objective (e.g. by lowering the targeted profit margin) but not his basic rationality (e.g. firms always aim at profits). Furthermore, an agent can adjust his set of routines, replacing one or several of them. Routines may be changed either due to the insufficient performance (the objective is not achieved) or in the course of forming an new organization, a case that is not considered in our present model.

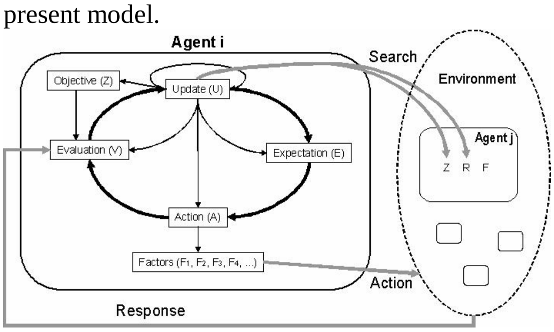

Figure 1. Evolution of a socio-economic agent

Evolution is based on an expectation - action - evaluation - update cycle which goes on continuously in any agent. If the evaluation of the results of past actions is unsatisfactory in relation to the stated targets, then the update rules are invoked which can change all of the routines (also the update routine itself) as well as the objective. Action rules are invoked by certain expectations and are executed by employing disposable production factors. In the case of a negative evaluation outcome, the agent looks for new routines. The search of new routines can either be global or restricted. We apply both types of search. Global search means that an agent screens all routines currently in use in his environment. In the case of restricted search the agent deliberately screens or can only access a selection of routines.

The agents in our model may differ with regard to the objectives as well the routines applied. It is impossible to describe the whole pool of objectives and routines in detail in this paper. The following chapters give only a short overview of the main characteristics of objectives and routines that are relevant for the agents.

2.1.1 Forestry

This is a heterogeneous category of agents, comprising small forest owners with little commercial interest as well as big forestry companies, run by a professional management.

The objective of any forestry agent is to make a profit from selling timber (reduced by a certain amount for own use, e.g. as fuelwood). The subsistence goal may be significant in the case of small owners while it is usually negligible in the case of forestry companies. Another source of heterogeneity are the actual profit target values. Some agents want to increase profits while others are satisfied keeping their profits constant.

Any forestry agent has at least three models forming expectations. One refers to the demand per quality of timber, another to the price per quality, and a third concerns the annual yield per quality (i.e. a combined stock-growth model of the forest in yield). Quality is (simplified) defined by species and shape of a tree.

In our present model we do not consider investment, i.e. enlarging the own forest area. This would be linked with organizational change which we have ruled out generally in the first model. So agents produce timber on a given area by applying different forest management methods. In the first version of the model we consider only the following methods: plantation, clear cutting (with reforestation or natural rejuvenation) and selective harvesting (with reforestation only if a relatively large number of trees are removed). A further simplification is that each method is only characterized by a specific combination of harvesting/removal and reforestation (and the related costs), neglecting maintenance efforts and technical issues of removal (e.g. machines used).

Evaluation is the comparison of realized and targeted profits. Update rules are invoked if the achievement of goals is not satisfactory. The update rules specify when objectives or routines have to be changed (thresholds), which are going to be changed and how they will be adjusted (e.g. by certain search rules).

2.1.2 Timber demanding industries

We consider the three most important timber demanding industries which are furniture manufacturing, construction and paper production.

All agents state certain profit targets which differ regarding margin and development (similar to the forestry agents). Each firm is active in one market only - either furniture, construction or paper. There are no diversified firms.

The agents use models predicting demand for wood products of different quality, prices of the respective goods and prices of the required timber. These models are based on some kind of past experience (e.g. average demand and price over a certain period), more elaborate forecasting methods are not included in the present model. Demand for wood products is exogenously given (e.g. constant, increasing market demand regimes).

Each firm has a plant-specific production function with a certain maximum capacity. Due to the same reasons as in the case of forestry we do not yet consider the possibility of investing in new capacity. Two industries have segmented markets - furniture and construction. We assume that both can produce high- and low-quality goods. In the case of furniture, for example, high quality products are made of beech or oak, lower quality uses pine, spruce or birch. For both, however, straight and long timber is required. In construction high quality (e.g. straight and long beech, oak, larch, fir) is required for buildings, floors, and similar products whereas low quality (branches, residue) is sufficient for boardings and particle boards. Paper production needs only cheap and fast growing timber like poplar, birch or spruce. In the present model we do not consider technological change. There is neither an increase in productivity nor the possibility to substitute lower for higher quality timber. Because we do not consider any differences regarding technology between the firms, costs of production other than the cost of buying timber can be neglected. What matters, on the contrary, are costs of transportation between the seller of the timber and the own manufacturing plant.

For evaluation and update rules the same as in the case of forestry applies in the general sense.

2.1.3 Communities

This class of agents comprises all administrative units at the local level. We do not consider the political process behind the behaviour of mayors and councils but regard the agent 'community' as if representing the collective interests of its population.

In our model the communities are only interested in the protection function of forests, i.e. preventing erosion or reducing the risk of avalanches in alpine regions. Other functions of forests like recreation and hunting are not considered in the first version of our model. Furthermore, we assume that no community practices commercial forestry. In order to fulfil the protection function, a forest has to be kept in a certain state (e.g. density and coverage, age and species structure). Communities expect that a certain state of a forest reduces the risk of natural disasters (of different frequency and magnitude) like landslides or avalanches.
A community can execute two actions: It can prescribe and enforce detailed management standards (e.g. ban of clear cutting), and it can directly influence the structure of those forests that are in communal property by respective maintenance and reforestation. Most forests in our model are privately owned, however, so communities have to rely primarily on standards as means of influence. If frequency and magnitude of natural disasters exceed the accepted limits, the respective community adjusts standards or maintenance and reforestation practices.

2.2 Interrelations between agents

The central interrelations between socio-economic agents in our first model are between timber suppliers and timber consumers, forming a timber market. In addition, communities influence forestry by setting standards according to the need for protection (see Figure 2).

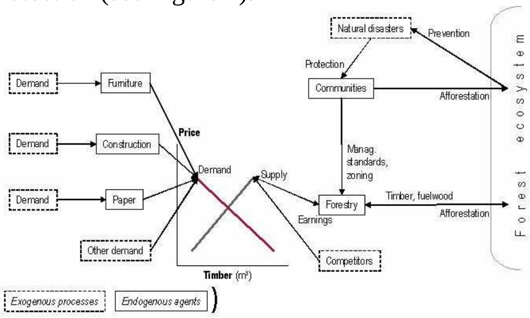

Figure 2. The socio-economic model determining the use of forest resources

2.2.1 Timber market

In our model the market is characterized by imperfect information and strategic behaviour. Prices are influenced by all the agents supplying as well as demanding timber. Each agent's behaviour depends on and affects all the other agents. Such market conditions can lead to a wide range of patterns, equilibrium is a possible but not a necessary outcome. Price and supply of timber are determined in a self-organized way:

Each forestry agent expects price (p) and demand (d) for each timber quality (q) of his available stock (v) of trees. The costs of extraction (c_x) depend on the management method. He ranks the quality classes according to the respective profits (p_q v_q - c_x v_q). Based on this ranking he removes trees from his stock, beginning with the most profitable class, up to expected demand or available stock (whatever is the actual limit). Summing up all these offers from the agents as well as from exogenous competitors leads to the total supply of timber differentiated by quality. Supply is then matched with demand (see next paragraph) and contracts are concluded when the offered price equals the accepted price for timber of a certain quality. Offers which cannot find any firm willing to buy at the proposed price are stored (reducing the volume to be removed in the next round). Based on the results, agents adjust their routines and the next cycle begins.

Each firm of the timber demanding industries expects demand (d) for and price (p) of its products, the price of timber of the required quality which, because it is the only input, equals the cost of production (c_q). Furniture manufacturers and construction firms can have two products, low- and high quality. They produce the more profitable good up to expected demand or maximum production capacity (whatever is the actual limit). If capacity exceeds demand for the more profitable product then the remaining capacity is used for the second good. Sales minus costs gives the profit. Costs comprise only timber and its transportation to the plant (p_q d_q - d_q (c_q + c_t)). Summing up all the timber demand from the agents as well as from exogenous demand leads to the total demand for timber differentiated by quality. Demand is then matched with supply (see previous paragraph) and contracts are concluded when the accepted price equals the price offered by the forestry agents. After having completed all the contracts, the firms produce the goods and try to sell them. This second-tier demand is exogenously given and determines the agents' success which enters the decision process in the next round. Firms can reduce their costs either by asserting lower prices of timber or by choosing more closely located forestry agents, reducing transportation cost c_t.

2.2.2 Protection function

The protection function is affected by a simple cycle: Extraction, reforestation (by forestry as well as communities) and natural growth determine the structure of the forest. This, in turn, determines its capacity to prevent natural disasters. This feeds back into the decision of communities whether to change standards and reforestation or not.

3. FOREST SUBSYSTEM

Natural ecosystems are generally undergoing changes and responding to changes, they are open, in flux and are affected by a series of often stochastic factors. For a sustainable management process scientific analysis and monitoring are therefore necessary [Schaffer, 1997]. An agent-based model can help to analyse the self-organization process during the forest ecosystem succession. Together with the monitoring of the key parameters within the forest ecosystem an adapted management can be established.

3.1 Agents in the forest model

Different trees with different main characteristics are the agents of the forest model. These agents are spatially fixed which means that they are not able to move during development, but their influence due to seed dispersal and competition with other trees goes beyond their local position. Within a forest succession dynamic there are differing types of species with differing characteristics. Pioneer species which have advantages at the beginning of settlement or resettlement of an area (e.g. a gap within a forest ecosystem after a windthrow) cannot compete with species later on in the succession dynamic. Existing old forest stands therefore often do not represent the biodiversity explored during the dynamic. For example, if we look at Austria's forest inventory, many species seem not necessary to be modelled because of their marginal occurrences. However, if we want to simulate the self-organization processes, they are of course, important too. At this stage of the model we include about 10 different tree species, but the future might show that we have to include more.

3.2 Self-organization in a forest ecosystem

A definition for self-organization in biological systems is given in Camazine, Deneubourg et al. [2001]: "Self-organization is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system." Within a forest ecosystem trees can be seen as lower-level components which act mainly local while their interaction shapes global patterns. One main problem of analysing changes in forest ecosystems is that visible changes of patterns often take a very long time. A computer-based simulation model therefore can provide a tool to observe these trends earlier and help to find more sustainable management decisions. One major goal is hence to capture the main events and mechanisms that determine the temporal and spatial dynamics within a forest succession under given environmental circumstances.

We use a simple but, as several studies have shown [Shugart and West, 1981; Green, 1989], efficient approach which is based on the forest model JABOWA III from Botkin et al. [Botkin, 1993]. In the model the trees are characterized by diameter (breast height diameter, BHD), height and species. Every species is defined by a set of parameters and they compete against the other to get more light, water and nitrogen. For every agent, every tree, the general growth equation is calculated (Equation 1).

$$\Delta GGF = f(D_{max}, H_{max}, b_2, b_3, D, G) * f(\text{environment}) \qquad (1)$$

This calculates the maximum growth potential (maximum changes) for each tree species, as a function of few parameters like the max. diameter or max. height this tree species can reach, reduced by local environmental responses, f(environment), which is a factor between 0 and 1. The environmental responses are correlated with the available light and the site conditions (Equation 2)

$$f(\text{environment}) = f(\text{light}) * Qi \qquad (2)$$

The site conditions include the general temperature response function TFi, the "wilt" factor WiFi, an index of the drought conditions a tree can withstand, the "soil wetness" factor WeFi, an index of the amount of water saturation of the soil a tree can withstand and the index of tree response to nitrogen content of the soil NFi (Equation 3).

$$Qi = TFi * WiFi * WeFi * NFi \qquad (3)$$

In a natural forest ecosystem dead trees belong to the common view and are a main entity, whereas they are often missing in a managed forest. This is important because some seeds chiefly germinate on old dead trees. Within the model mortality will be simulated accordingly to JABOWA III in two different ways.
First, there is an inherent risk of death for any tree, independent of the competition with other trees, e.g. the death due to a windthrow, or, also very important as interrelation to the socio-economic subsystem, via harvesting, which will be discussed later on.
Second, there is competition-induced death. Trees that grow badly over a certain period of time (e.g. ten years) have a higher probability to die than well growing trees.

These are the responses of an existing tree to the environment, but the natural reproduction of trees, i.e. rejuvenation, is also very important. A tree has to reach a kind-specific age for seed production and produces characteristic seeds. To simplify the model, we distinguish only between shade-tolerant, intermediate and shade-intolerant seeds. Different to the forest model developed by Botkin et al. [1993] (JABOWA III), we don't assume that there are always enough trees to produce seeds independent of the management practice and how many old trees are in the area able to produce seeds. We think that this fits more to the reality and as other investigations have shown, special events as increased seed production in the same time with increased open areas might influence strongly the dynamic [Wiegand, Milton and Wissel 1995]. In the first approach we assume concentric dispersal of the seeds from the producing tree, but the model could be improved by correlating the seed dispersion with the main wind direction.

Self-organization within the forest succession model emerges due to indirect local competition of the trees for light (f(environment)) and space (seed dispersal). An indirect competition for nutrients and water is not implemented in the present version as one tree does not influences the general availability of nitrogen and water of a neighbouring tree.

3.3 Parameterization and validation

Parameterization of models is one of the crucial steps in the development of a model. One reason to use a relatively simple model approach is to find valuable data for parameterization. Main inputs for the forest self-organization model are the tree characteristics, the site conditions and information about stochastic events like windthrow, seed dispersal or tree mortality. At the present stage of the model there are no feedbacks from forest to the occurrences of calamities like from bark-beetle. The validation of the dynamic behaviour of the forest subsystem has to be done intensively to prove the reliability of the simple model approach.

The validation process itself can be described in a three step procedure:
First, the potential growth curve of each tree species has to be simulated independently from competition with other trees.
Second, the different environmental response function of each tree species has to be checked independently.
Third, the competition between different tree species has to be analysed.

The results of these three steps have to be discussed with experts and compared with the development of existing natural forest ecosystems in Austria before the connection with the socio-economic model.

The environmental influences described above can be summarized as *external natural influences,* which are often stochastic events, difficult or even impossible to predict. They can occur in unmanaged natural as well as in managed forests. The interrelation to the socio-economic subsystem is simulated due to the so called *external human influences*. The positive feedback between *Ability to compete with other trees*, *Resources* and the *General growth function* characterizes the self-organization process (Figure 3).

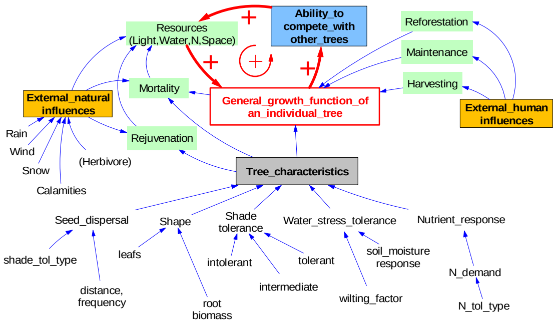

Figure 3. General forest model scheme

4. THE TOTAL MODEL

The total model helps to identify the key self-organization processes in the socio-economic and the ecological systems and the feedback relations between them. This knowledge enables adaptive management to better target its activities on the most crucial processes and at the right time. Three types of interaction link both models − removal (harvesting), reforestation and maintenance. In the present version of the model only the first two are considered (except for a rudimentary role regarding the protection function for communities, see chapter 2.1.3).

Removal, harvesting: Timber for different purposes like furniture, construction and paper production require different tree species with different qualities like age, shape or BHD. Demand, determined in the socio-economic subsystem, provides the information which trees at what location and by which harvesting method will be removed. In the present model there are only very simplified versions of management methods (plantation, selective harvesting and clear cutting, see chapter 2.1.1). Further impacts of harvesting (e.g. on the soil) are not yet considered.

Reforestation: From the socio-economic subsystem information is provided which tree species when and where should be planted. Reforestation has no direct influence on the general growth function (ΔGGF) of existing trees, but affects them indirectly, because competition for resources by newly planted trees also affect existing trees.

5. OUTLOOK

The model presented in this paper is simplified and we don't know yet whether our self-organization model will really enable us to analyse the key processes for the adaptive management of renewable resources. Further necessary improvements could be:

- Adding new types of agents (e.g. hunting, tourism, deer, bark-beetle, wild boar).
- Including other forest functions like recreation.
- Incorporating the evolution of agents (e.g. setting up new organizations) in the model.
- Making the agents' strategies more realistic.
- Considering the role of technology and technological change.
- Integrating GIS data (e.g. topography, elevation) to specify the environmental response functions (e.g. temperature, light, soil moisture).
- Choice of an appropriate modelling software e.g. NetLogo, RePast, Swarm.

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