

Disturbance and Succession – Potential of Agent-based Systems for Modelling Vulnerable Ecosystems

Application to Land Degradation Processes

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Abstract

Multi-agent-systems (MAS) and Cellular Automata (CA) allow not only the schematic simulation of environmental processes but also the integration of real datasets and biological knowledge. This combination can be an effective method for the modelling of the behaviour and development of vegetation after strong land disturbance. This study is a bottom-up approach creating a model which is able to integrate different kinds of data in order to simulate the process of secondary plant succession. It can be supplemented and adapted according to the interest of the modeller and to the study area and its regional conditions. Though there are still some hurdles to be got over, it has nevertheless been a successful first attempt for further investigations to gain information about the process of land degradation that occurred in the Chinese province of Yunnan due to intensive copper-mining during the Qing Dynasty (1644-1912).

1 Introduction

Multi-agent-systems and Cellular Automata are effective tools for simulation processes in almost any branch of science. Their application in the field of geography is not completely new but is, as yet, restricted to certain branches of research (KOCH & MANDL 2003). In contrast to classical GIS-analyses, which are more static and dependent on input data, MAS and CA are able to start and continue processes with information which they have generated themselves. The main reasons for the infrequent application of MAS within scientific studies until now could be their experimental character and their lack of ability to integrate different kinds of data. However, technological progress and trends towards standardization now offer new possibilities of working with these technologies.

This study examines whether MAS have already been well enough developed to enable simulation of the ecological processes which take place after strong land disturbance, in particular the progress of vegetation succession and the way in which different influencing parameters can be integrated. The aim was to run a showcase simulation, based on real datasets and on biological knowledge about the behaviour of vegetation in the region of Yunnan, southwest China. A suitable modelling approach can thereby be developed, to reconstruct or predict processes of succession. However, the study intends to deliver a simple and cost-effective method which can be upgraded according to the focus of later

studies. So the used datasets are not the best suitable ones yet but at least they are disposable easily and fulfil the task of investigating the capabilities of MAS. At the same time, potential problems and technical barriers can be identified in order to improve the development of these kinds of systems.

2 Multi-agent Systems

Agent-based modelling has been in development since the 1980s as a sideline of the explorations of artificial intelligence (OPENSHAW 1997). It can be understood as being a raster fundament, representing an artificial environment. Each raster cell is called a *patch* and contains all the various kinds of information needed to express the corresponding system and its attributes (see figure 1). The difference between typical CA and MAS lies in the so-called agents, which are defined as active units within this system. They are able to move across the patches, read their information and align their own behaviour based on this and additional information. These agents are thus independent on the one hand, but also follow given rules and conditions on the other (BOMAN & HOLM 2004). Over the years the expression *turtles* has become established, and this will be used in the following. The application's programmer is called the *observer*. He defines the set of information and how it is expressed as patches. He also constitutes the behaviour of the turtles by setting up a framework rules and conditions.

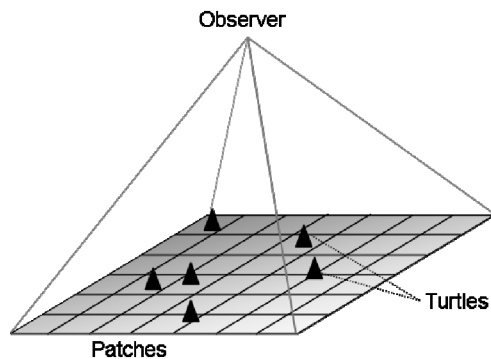


Fig. 1:
Schematic composition of MAS
consisting of turtles, patches and
the observer.

3 Application

3.1 Software, Input Data and Model Design

The software which was used for this research is NetLogo (WILENSKY 1999), an open-source modelling software developed at the North-western University's Centre for Connected Learning and Computer-Based Modelling. It has been regularly updated and improved since its first release in 1999. An important further step was the development of a GIS-extension in 2008 which enables the import and export of vector and raster GIS-data. This additional data can supplement the modelling process by adding more information to the simulation, such as maps, numerical data or even Digital Elevation Models (DEMs).

Furthermore, simple tools such as raster mathematics, intersections or spatial queries can be used within the programme. This enables us to use the combination of geographic located information with complex modelling simulation.

The Chinese province Yunnan has been chosen as the study area in order to continue the research of ROSNER & DIEBALL (2010) and FOR596 (2010; see references). Covering approximately 394,000 km² in the south of the country, it was a centre of the copper mining industry from the 17th century until early 20th century. However, only a small amount of data is available on the amount of mining activity and on the associated deforestation, which provided lumber for the mining galleries and wood for metallurgical processes. This modelling is thus an attempt to answer questions about the development of degradation and vegetation succession and can be extended with various kinds of information into on-going research projects.

The additional data used in this research was a 1 km-DEM by the U.S. Geological Service (USGS 1998) and a 1-km land cover classification (HANSEN et al. 1998). Even though this is not the ideal resolution for these regionally-scaled vegetation processes, the study should be based on open-source data in order to demonstrate that even common data can deliver satisfactory results when used in combination with MAS. Furthermore, a successful modelling approach can be taken further at a later time with better data.

So, according to figure 1, there are more objects available that contain information. Figure 2 summarizes possible ways in which conditions and processes can be expressed within the model. Note that layer 2 “Numerical Information of Patches” can contain more than one type of data within each patch.

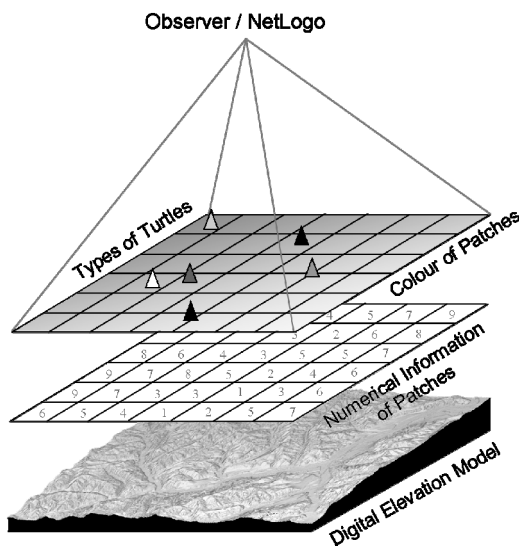


Fig. 2:
Carriers of information in the
extended modelling environment

The next step, and a primary question of the simulation, was to decide how to express the biological elements with the various containers of information. In order to cope with the complexity of plant succession, a suitable choice seemed to be to define the patches' colour

as land cover and the turtles' as the plant seeds, which follow specific rules of spreading. The DEM delivers the information needed to characterize the relief, which also has an influence on plant succession. Finally, various kinds of numerical information were inserted into the patches in order to give the necessary information to keep the model running. Table 1 gives an overview of the distribution of data across the modelling elements.

Table 1: Overview on the elements used for the simulation.

Carrier of Information	NetLogo element
Types of turtles	Seeds of the different plant communities
Colour of patches	Types of land cover and vegetation
Numerical information of patches	Control factors and parameters for the simulation
Digital Elevation Model	Height, slope and aspect of the terrain

3.2 Preconditions for Succession

The rules which define the process of succession after disturbance are based on biological knowledge of plant reproduction and spread. They have intentionally been kept simple so that evidence of their influence on the simulation can be clearly seen. However, they can easily be further specified at a later date, in order to adapt the model to more realistic circumstances. The model proceeds according to the following points:

- **Biological fundament:** Succession underlies the Relay Floristics-approach (FISCHER 2003) which determines that the various different types of vegetation (e.g. grass, shrubs, woodland) start growing one after the other.
- **Direction of redistribution:** It is assumed that the spread of plant seeds is more likely to go downhill than uphill. Only when transported via animals their spread direction ceases to follow any physical rules, so we have to reckon with a small element of chance.
- **Speed of redistribution:** It is furthermore assumed that, following the simple rules of physics, the spread of plant seeds goes faster downhill than uphill, when carried by water or wind.
- **Influence of insolation:** Pioneer plants (e.g. grass and herbage) are more adapted to sunlight and therefore spread faster in sun-exposed areas. In turn, later successive plants like shrubs and trees prefer more shaded growing conditions, under which they are able to grow and spread more quickly.
- **Climax communities in different elevations:** The elevation of the terrain extends from 510 to 4250 metres and thus provides differing climatic growing conditions. The various different climax communities (e.g. deciduous forest, mixed forest, evergreen forest) will tend to develop at corresponding levels of elevation. A statistical analysis gave percentage values for each community's likelihood of occurrence in a corresponding site of the terrain.

3.3 Implementation

The programming language of NetLogo is based on pre-defined elements such as keywords, constants, commands or reporters, but also leaves the user enough space to express own commands and algorithms. In the case of this study, these consist of mathematical equations and various if-then clauses.

Due to the fact that the focus of the model lies on the process of succession, the disturbance is represented as a radial deforestation, at a user-defined spot in the terrain. Land use classes which cannot provide lumber, such as agricultural land or urban areas, are not affected by the deforestation process. From patches at the boundary of this area, defined as *Initial-Patches*, the first turtles start to move across the deforested areas in order to repopulate them. At first their direction of movement is random, but subsequently the direction and speed of movement are defined by a decision tree (see figure 3), according to the rules in 3.2 and the parameters of the terrain.

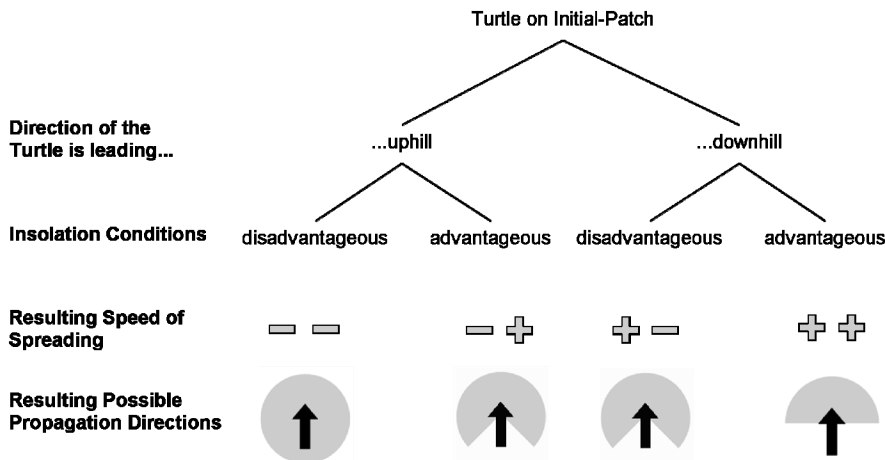


Fig. 3: Decision tree expressing direction and speed of movement of the plant seeds. Plus and minus signs represent the influence of the previous parameters on the spreading speed. The radial grey area defines the range of possible directions of movement for each subsequent step of the turtles.

So it is assured that insolation conditions and physical terrain parameters have a common effect on spreading behaviour, and also that the direction of movement is more likely to be maintained under advantageous spreading conditions. Slopes of the terrain have been classified according to differing strengths of influence on the speed of redistribution. Finally, the different stages of vegetation development had to be implemented. The model is restricted to the three stages – grassland, shrubland and woodland – according to the recovery model of LI, YANG & WU (2008). The last of these, representing the climax stage, is further divided into five classes – evergreen forest, deciduous forest, mixed forest, woodland and wooded grassland. A spatial analysis was used to calculate which climax stages are statistically supposable for each spot in the terrain. So, if an area is more suitable for

shrubland, no climax stage will arise there at all. Otherwise, a check was carried out to establish which climax stage would be most suitable for this place. This process (see figure 4) was executed for every patch that had been deforested and has now been colonized again by turtles, by the respective seeds of the surrounding vegetation.

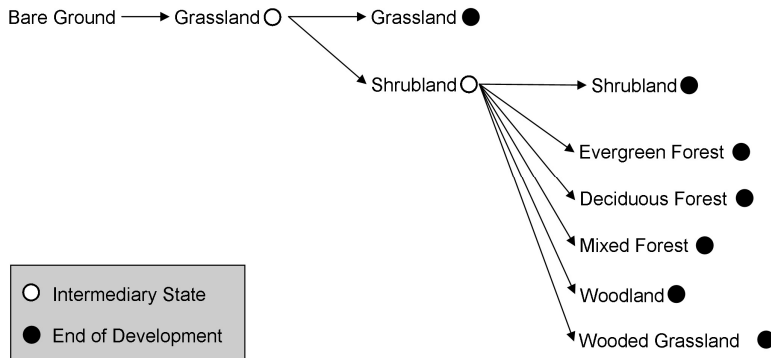


Fig. 4: Sequence of possible vegetation development according to growing conditions

4 Results and Discussion

After importing the land use and elevation datasets and defining spots for deforestation, the model could be started. In order to see a difference between unequal topographic conditions, two sites in extreme positions (see figure 5) were selected: The bottom of a valley (A) and a topographic culmination (B).

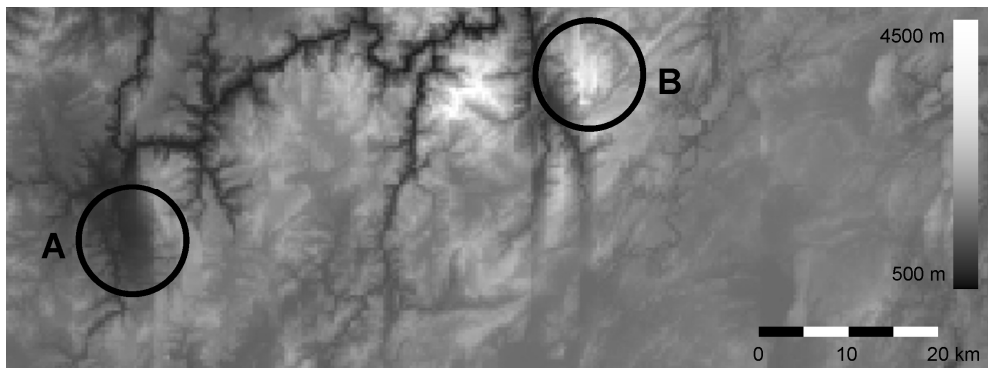


Fig. 5: Definition of two sites in the area for deforestation in order to show differences between unequal topographic conditions and their influences on succession

The two sites contain large areas of agricultural land and were chosen as such in order to demonstrate that non-vegetation land use is neither affected by logging, nor does it influence succession processes. These areas can be seen in figure 6 as lighter sections within

the black deforested areas. The other grey tones represent the various different stages of succession and their corresponding plant communities. After 25 years you can see the development of shrubland (dark patches) at the edge of the circular area, which then develops into various kinds of forest at later times. Figure 6 also shows that succession progresses faster within site A, where the spreading goes mainly downhill. In addition to this, slopes with greater gradients show a faster spread. After a period of 50 years, Site A is almost fully-covered, at least with grassland, while within Site B there are still large areas with no vegetation at all.

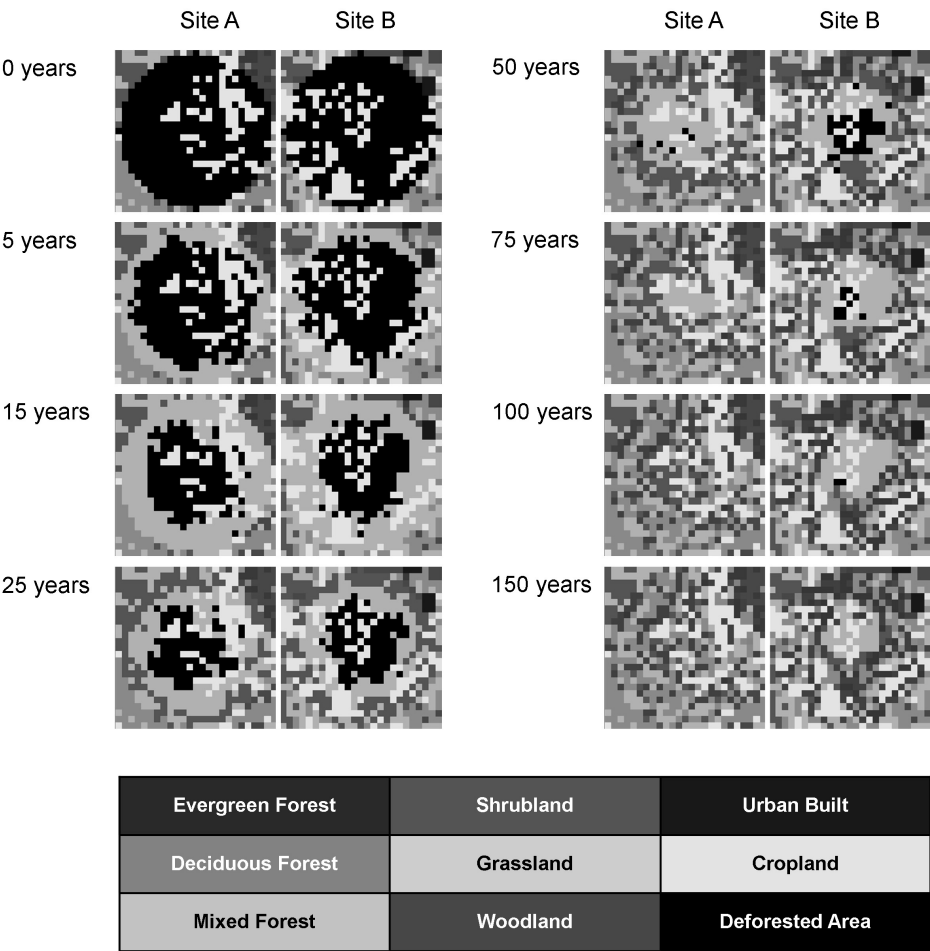


Fig. 6: Simulation results at discrete time steps. Note that the light parts within the deforested areas (black) are agricultural land which is not influenced by deforestation or succession. All other grey tones represent the different stages of succession and their corresponding plant communities (according to figure 4).

A number of different simulation runs showed similar results to those described and demonstrated above. It became clear that we had been able to adapt all the relief parameters successfully. The percentage of area of the different plant communities after the completed succession could be compared to the values before the disturbance. However, statistical occurrence of the different climax stages, as described in 3.3, is not founded well enough within the model yet. More detailed knowledge of growing conditions and behaviour, according to the site parameters, such as soil or proximate plant communities, is provided by TANG (2010) and LI, YANG & WU (2008) and its inclusion has already been planned. Nevertheless, the succession pathways and their different degrees of speed could be implemented successfully.

5 Conclusion and Outlook

Multi-agent-systems are effective tools for the modelling of environmental changes. Several studies have already showed that they can be applied successfully in terms of forest change (EVANS & KELLEY 2008; CHAVE 1999; PAUSAS 2006) in order to gain insights about the behaviour of the system of interest. These are commonly called ‘exploratory models’ (PERRY & MILLINGTON 2008). However, this study showed that they can also fulfil tasks of prediction as well and allow the integration of different kinds of datasets and to implement biological knowledge into models. All preconditions can be successfully included and have an influence on the simulation. Of course the assumptions are still quite speculative, because they could not have been validated yet. Accordingly, as soon as there are land cover datasets of the 17th century (see below), a way of validating needs to be found in order to support the gained information. ZELLNER (2008) names two main challenges in dynamic modelling: complexity and uncertainty. At least the first one could have been managed quite well so far. There are still a number of points that could be enhanced, but nevertheless, the approach provides an adequate basis for more sophisticated models in the future. We have to point out here that no universally valid model can be created. Each model has to be adapted to regional situations and to the spatial scale of the processes being investigated. The focus of the model thus needs to be defined at the very beginning of its development. Taking these demands into consideration, MAS provide almost infinite possibilities for the implementation of biological and ecological processes into models. The success of the modelling depends simply on the creativity and sense of logic of the person implementing it, and this person needs to be able to understand the programming language, as well as ecological, biological and climatological systems and their interrelations. Such tasks can be dealt with by the interdisciplinary sciences.

We are looking forward to turning this approach into a more sophisticated simulation:

- Finding an optimal level of spatial resolution and integration of more suitable datasets for a more precise investigation.
- Integration of land cover data representing the conditions of Yunnan in the 17th century (HAGENSIEKER 2010).
- Consideration of anisotropic deforestation, according to topography and transportation routes (ROSNER & DIEBALL 2009).
- Neighbourhood effects on the development of plant communities as climax stages (TANG 2010).

- Development of a validation method for later achieved results. GRIMM et al. (2005) propose to use pattern oriented modelling with MAS which can help to find emergence underlying the system. These structures can support the process of modelling as well as the testing of the simulations.
- Combining NetLogo with software R for better statistical approaches with the datasets (THIELE & GRIMM 2010).

This leads us towards a more holistic approach which is able to draw a balance between the output of the copper mines and their effect on the natural environment. This can be done by integrating the different growing rates of vegetation, and by considering how much lumber can be gained from each plant community. In addition the influence of population distribution and agriculture on the natural resources, as it was presented by BERGER (2005), can also be added at a later time. With a solid foundation, such as is presented in this study, the model can be expanded step by step.

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