Application of Cellular Automata in Conservation Biology and Environmental Management[1]

Miklós Bulla, Éva V. P. Rácz

Széchenyi István University, Department of Environmental Engineering, 9026 Győr Egyetem tér 1., Hungary, e-mail: bullam@sze.hu, raczev@sze

Abstract:
Cellular automata are reliable tools of spatiotemporal modelling and widely used in several fields of natural sciences. As they are based on local rules of interactions they are particularly applicable for conservation biological and environmental management's problems. Human impact on natural ecosystems is studied with the help of such models. Colonization ability and spatial patterns of the species are shown to have a remarkable role on the outcome of human-nature interaction.

Keywords: cellular automata, environmental status assessment, invasive species, competition, spatial patterns

1 Introduction

Demands of human civilization from natural resources are still continuously increasing, and paralelly human's effect on its environment as well.
At the same time there is a need of sustainability of natural resources and a good quality of environment. The duty of environmental management is to create balance between these two contradictions; human needs and natural resources.
In order to manage this equilibrium it is necessary to have information about the current state of the environment and competent tools for predicting possible changes of this state due to diverse effects. Manifold processes have to be investigated within each media of the environment (air, water, soil, nature) and also among them [1, 2].

In this article we concentrate on the media "nature", and human impact on it.

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The most radical and visible human effect on nature is habitat destruction. As a consequence of habitat destruction damage in natural systems is not restricted to loss of the physical space. Most cases it comes with fragmentation that means the ratio of border areas will be higher even in the intact habitat areas. So it alters the intact habitats and has an effect on the processes inside them for example competition circumstances. It is proved that as the level of destruction is increasing weed like species get more advantage [3, 4].

Another well-marked effect of human is the emergence of alien invasive species. This species get to places far from their native land with human help – sometimes on purpose, sometimes against it. Some of them cause diseases or thin native species as predator or competitor.
The effect of invasive species on economics is outstanding. The approximated damage caused by invasive species only in the US is over 138 billion \$/year and 55-248 billion \$/year in the agriculture of the word [5]. Invasive species are also present in Europe, in Hungary e. g. the milkweed (*Asclepias scyriaca*) and the zebra mussel (*Dreissena polymorpha*) are the most familiar invaders. There is no good solution of this problem. Eradication is expensive it can also be dangerous (e.g. for other species) and in many cases practically impossible.

As this processes in ecosystems are hardly reversible and reproducible and they are often extended in space and for in time, there is fun possibility to make field experiments.
Although natural catastrophes and human irresponsibility generates some experiments but they are unplanned and one-shot.
Mathematical models and computer simulations are capable of investigating human caused and natural processes in ecosystems.

2 Models

2.1 Cellular automata

Cellular automata are flexible and particularly useful for spatiotemporal investigation of natural processes. They are also widely used in miscellaneous scientific problems (e. g. flow dynamics, biochemical reactions, tumour growth [6,7] etc.). Their reliability originates from the structure that global behaviour is deduced from local rules.

The conception of cellular automata is based on the original idea of John von Neumann [8]. The following modern definition is used widely both in theoretical and applied sciences.

Definition of cellular automata

A cellular automaton $A = \langle L, S, \rho, \psi \rangle$ consists of a cell-space L with a neighbourhood relation ρ, a set of states S and a local transition (or update) function ψ. The cell space is usually a lattice (e. g. a discretized physical space Z^n, $n \in Z^+$ dimensional squared lattice). The most frequently used neighbourhood relations on square grids are the Neumann neighbourhood containing the four adjacent cells (North, East, South and West) and the Moorian neighbourhood consisting of eight adjacent cells (including North-East, South-East, South-West and North-West as well). Each element x of the cell space has a value $s_t(x) \in S$ at a given t, where the time scale is discrete ($t = 0,1,2,\dots$). The state of the cell at the next step $s_{t+1}(x) \in S$ is determined by the update function depending on both the actual state of the cell itself and on its neighbours' state:

$$s_{t+1}(x) = \psi(s_t(x), \{s_t(y) : (x, y) \in \rho\}) \quad (1)$$

The update function can be either deterministic or stochastic and applied synchronously or asynchronously (one by one cell) to the cell space. The models we investigate are stochastic synchronously updated CA defined on a finite square grid cell space with a torus topology at the edges and with Moorian neighbourhood.

Such models are particularly appropriate for natural dimension of environmental status assessment, because the traditional descriptive methods based on plant communities which can be considered discrete both in time (because of annual reproductive cycle) and space (based on either individuals or habitat patches). The feature of cellular automata that their rules originate from local relations opens an opportunity to approach field situations since local colonization and extinction (mortality) can be more easily handled than global processes.

2.2 Cellular automata model of spread and eradication of invasive species

We use single species cellular automata models for investigation of human effect on one species. Consider the interaction between human and an invasive species. Despite all effort new alien species appear time and again. Every vehicle we use to clamp distances can became a device of spreading other species as well. They arrive and begin to colonize new territories in an exponentially accelerative way. In some cases attempt to eradication is initiated relatively early stadium (when 5-10% of habitable sites are occupied by the non-indigenous species), but mostly intervention starts only when they are far too abundant (50-80%).

In order to compare this cases and a set of eradication strategies consider the following cellular automaton model based on the extensively used, classical metapopulation[2] model of Levins [12].His model assumes an infinite amount of uniform habitable patches, the change of the fraction of occupied patches denoted by p is described by the following equation:

$$\frac{dp}{dt} = cp(1-p) - ep \,, \tag{2}$$

where the colonization is proportional to $p(1-p)$ and the mortality is proportional to p itself, and the colonization and mortality rates exhibited of the species are c and e, respectively.

A cellular automata version provides a more realistic (spatially explicit) model in which colonization of a site (habitat patch) depends not on the proportion of occupied patches in the whole system but only on the state of its neighbours. Each site has one of the two possible states (empty (0) or occupied by the studied species (s)) in each time step. For the next step this state can change according to the update function

$$\psi(0,\mathbf{n}) = \begin{cases} 0 & \mathrm{P}(0 \to 0) = 1 - \mathrm{C}(\mathrm{N_s}) \\ \mathrm{s} & \mathrm{P}(0 \to s) = \mathrm{C}(\mathrm{N_s}) \end{cases}, \ \psi(s,\mathbf{n}) = \begin{cases} 0 & \mathrm{P}(\mathrm{s} \to 0) = \mathrm{E} \\ \mathrm{s} & \mathrm{P}(\mathrm{s} \to s) = 1 - \mathrm{E} \end{cases}, \tag{3}$$

where $\mathbf{n}$ denotes the vector containing the states of the neighbours of the actual cell, C the colonization function of $\mathrm{N_s}$, the number of the occupied neighbours and E the extinction function (independent of the adjacent patches in our model).

There can be several eradication strategies. From the models point of view they can classify into two categories:

- eradication without any influence on colonization (e. g. late cropping, cutting out trees after seed dispersal)
- eradication with deducing colonization capabilities (e. g. early cropping, shooing out individuals before reproductive period).

Eradication without influence on colonization

The first type of treatment manifests in our model by transforming the extinction function. Instead of constant extinction rate we can get a lower extinction rate by cutting out the same fraction of the individuals or cleaning out the same fraction of occupied patches year by year.

In most cases the percentage of cleaned patches cannot be considered constant in time. There is an eradication project, or from the spontaneous reaction of

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[2] A metapopulation is a system of interacting populations living on a set of habitable patches. For more details see e. g. [9].

inhabitants. We investigated linear[3] growing and increasing functions and exponentially saturating extinction functions (of time) and compared to constant and sporadic occurring every second, third, fourth etc. years but with same intensity eradications.

Simulation results display no observable difference between cellular automata having different extinction functions in their updating rule. The breakdown of arresting invasion is hardly influenced by its incidence rate at the beginning of the eradication.

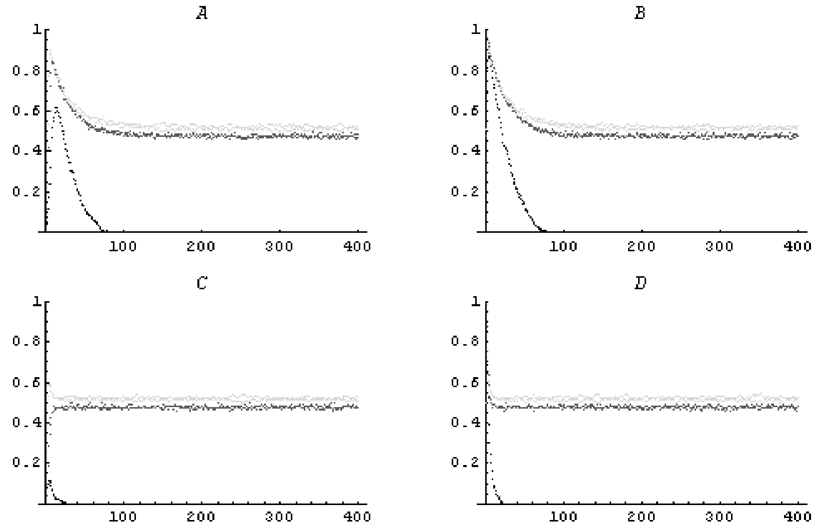

Figure 1. Temporal dynamics of fraction of occupied patches in case of four eradication strategy.
Each graph show three simulation results applying colonization function $C(N_s) = k\,N_s$, $k = 0.1, 0.2, 0.6$ respectively. Both in case of fast $E(t) = 0.9(1-(1-0.3)^x) + 0.01$ (A and B) and slow saturating extinction functions $E(t) = 0.9(1-(1-0.03)^x) + 0.01$ (C and D) no considerable difference can be observed between the two cases of treatment's start early (5 % occupied) see A and C and late (50% occupied) see B and D.

If the colonization ability of the invasive species is high enough even 90 % efficient eradication is not able to stop spreading alien. Huge amount of effort year by year can only keep the equilibrium abundance slightly lower.

[3] but necessarily bounded (maximum is not greater than 100%)

Eradication with preventing colonization

More useful manipulations can alter not only the probability of local extinction but reduce colonization ability. Strategies of this type are far more proper. In this case both from ecological and economical point of view not at all the same when the treatment starts.

Figure 2 shows an example when colonization functions $\mathrm{C}(\mathrm{N_s}) = \mathrm{k}\ \mathrm{N_s}$, $k = 0.2, 0.14, 0.05, 0.01$ decrease as a result of eradication process coming with fast saturating extinction function $E(t) = 0.9(1-(1-0.3)^x) + 0.01$.

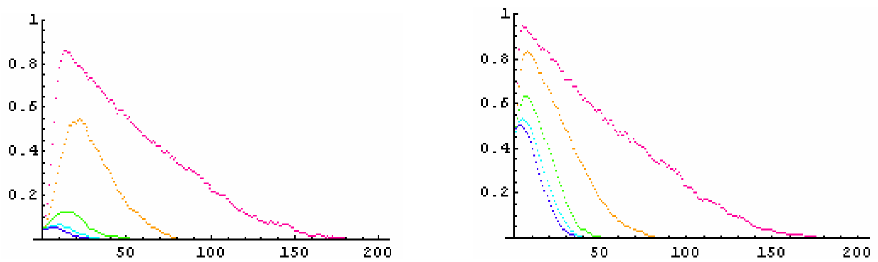

Figure 2. Temporal dynamics of proportion of occupied habitat patches in case of reduced colonization ability during eradication process.

In the first period of the process there is a greatly higher abundance of the invasive species in case of the late strategy, consequently the cost of the manipulation and the damage in ecosystem is more remarkable.

Conclusions

Media of environmental system have to be investigated one by one and together with their interactions among each other. Spatially explicit models are reliable tools to understand the dynamics of the subsystems. Cellular automata are particularly reliable for describing ecosystems because of their discreteness in space and time.

Simulations of one species cellular automata models show that colonization is the main determinative feature in suppressing of fast spreading alien species. The success of eradication depends on the possibility of reducing the colonization ability of the invasive species. The damage cased by the alien species to ecosystem can be decreased by eradication process initiated right time.

These models can be used as a basis of more species models to investigate different effects on species interactions [10,11].

References

[1] S. Kerekes and M. Bulla: Environmental Management in Hungary, Environmental Impact Assessment Review, Boston-New York, (1994), pp.14.

[2] M. Bulla, P. Keresztes, L. T. Kóczy: Applying Soft Computing Methods for the Analysis of Environmental Processes, International Conference on Computational Cybernetics, 2003.

[3] É. V. Rácz and J. Karsai: Computer Simulations on Cellular Automata Models of Metapopulations in Conservation Biology, Hungarian Electronic Journal. ENV-011125-A.

[4] S. Nee and R. May: Dynamics of Metapopulations: Habitat Destruction and Competitive Coexistence, J. Animal Ecology, 61 (1992), 37-40.

[5] Pimentel, D. et al.: Environmental and economic costs associated with non-indigenous species in the United States. Bioscience 50 (1), (2000), 53-64

[6] S. Wolfram: Theory and Applications of Cellular Automata, World Scientific, Singapore, 1986.

[7] T. Czárán: Spatiotemporal Models of Population and Community Dynamics, Chapman & Hall, London, 1998.

[8] J. von Neumann: Theory of Self-reproducing Automata, University of Illinois Press, Urbana, 1966.

[9] I. Hanski: Metapopulation Ecology, Oxford University Press, Oxford, 1999.

[10] É. V. P. Rácz and J. Karsai: Computer Simulation Results for Cellular Automata Models of Some Ecological Systems, Folia FSN Universitatis Masarykianae Brunensis, Mathematica 13 (2002), pp. 213-221.

[11] É. V. P. Rácz and M. Bulla: Cellular Automata Models of Environmental Processes, Proceedings of the International Conference in Memoriam John von Neumann (2003), 109-119.