Cellular Automata Models of Environmental Processes[1]

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Abstract:
The duty of environmental management is to create balance between increasing demands of civilization and natural resources. For this challenge there is an essential need of information about the current state of the environment and tools for predictions how the state would be change for different effects. Several processes have to be taken into account in each layers of the environment (air, water, soil, nature). Interaction of human and environment is investigated in every layer. Here we present some examples how cellular automata can be used for exploration of human impact on ecosystems, notedly on competitions of plants. Facility of arresting invasive species and the role of spatial patterns are investigated. This simulation results demonstrate the importance of spatial patterns. Spatial distribution can even change the outcome of the competition.

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

1   Introduction

1.1 Environmental management

Demands of human society and its impact on the environment are simultaneously increasing. From the sustainability's point of view it is essential to create balance between human needs and natural resources. This is the environmental management's main duty including several different but closely related tasks [1, 2]. In order to manage them, it is necessary to have information about the actual

state of the environment and reliable tools for predicting the possible changes due to diverse (both anthropogenic and natural) effects. Manifold processes have to be investigated within each media of environment and also among them. Clearly environmental systems cannot be divided into separate layers (as living micro-organisms are integral parts of the soil), but for the analysis of the system it is expedient to partition into subsystems air, soil, water and nature. In this article we concentrate on the "layer nature".

1.2 Human impact on nature

Alike on the other media of environmental system, human activities have extensive impact on nature. The most visible effects are direct habitat destructions e. g. by generating infrastructural elements. As a consequence of destroying a habitat area, nature lost more then the actual physical space. In most cases habitat destruction alters the spatial structure of the landscape [3]. Instead of large continuous areas it creates separate small patches preventing migrations. The border area is also enlarged making the ecosystem more fragile. It is well underpinned, that invasive species have the advantage of native species in competition as the number of unsuitable habitat patches increases [4]. Non-indigenous invading species get far from their original living area, sometimes on purpose sometimes despite of it, but in each and every case with human help. The estimated damages and losses caused by them are adding up to more than $138 billion per year in the US [5]. The problem is not confined to the new world; it is also present in Europe, in Hungary (e. g. milkweed (*Asclepias scyriaca*), zebra mussel (*Dreissena polymorpha*) just to mention the most familiar invaders). There is no good solution; eradication is expensive, dangerous and in many cases practically impossible.

Natural processes on landscape level are hardly reversible and reproducible and their timescale is far too much slower than we could make field experiments. Mathematical models and computer simulation enables to investigate progressions of decades in some minutes, trying out and comparing different possible alternates of maintenances, operations and projects.

2 Cellular automata

Cellular automata are flexible tools to approach spatiotemporal dynamics therefore they are widely used in miscellaneous scientific problems (e. g. flow dynamics, biochemical reactions, tumour growth [6-9] etc.). Their reliability originates from the structure that global behaviour is deduced from local rules. John von Neumann, the father of the idea of cellular automata has already

foreknown, his creatures would play a considerable role in natural sciences [10]. As the performance and availability of computers supported, it came off indeed.

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 ($t = 0,1,2,\ldots$). 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:

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

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.

3. Model of spread and eradication of invasive species

At first consider only the interaction between human and the 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 automata 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 is in one of the two possible states (empty (0) or occupied by the studied species (s)) in every time step. For the next step this state can change according to the update function

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

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

There are 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 the 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.

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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. [11].

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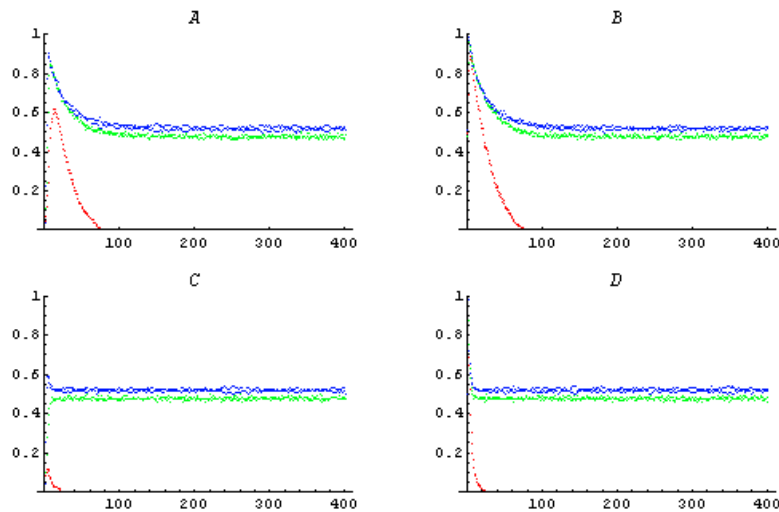

Figure 1. Temporal dynamics of fraction of occupied patches in case of four eradication strategy. Each graph show three simulation results applying colonization function $C(N_s) = k\,N_s$, $k = 0.1, 0.2, 0.6$ respectively. Both in case of fast $E(t) = 0.9(1 - (1 - 0.3)^x) + 0.01$ (A and B) and slow saturating 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 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.

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[3] but necessarily bounded

Eradication with preventing colonization

Manipulation often alters not only the probability of local extinction but can reduce colonization ability. Strategies of this type are far more proper. 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 fall of to $C(N_s) = k\, N_s$, $k = 0.2, 0.14, 0.05, 0.01$ as a result of eradication process coming with fast saturating extinction function $E(t) = 0.9(1 - (1 - 0.3)^x) + 0.01$.
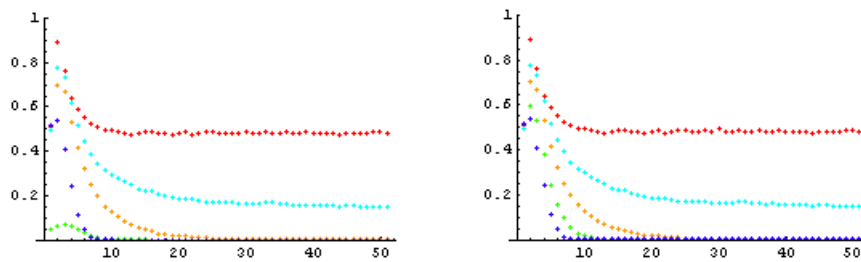

Figure 2. Temporal dynamics of proportion of occupied habitat patches in case of reduced colonization ability during eradication process.

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

4. Two species competition model

The effect on the ecosystem can be investigated in some measure with the help of two species models. In a healthy natural system resources are well distribute among species. Forcefully spreading species can directly violate native species through competition what can be investigated by adequate models.

The model we developed for studying spatial interactions between species [13] is a generalization of the one species cellular automata model introduced in the previous chapter. It can be treated as a spatial version of two species Levins model [4].

We consider a finite sufficiently large square grid with periodic boundary conditions representing a peace of landscape with habitable patches. Two species

are competing for the resources, accordingly the state of each cell (patch) can be empty or occupied by the first (1) or the second (i) species[4].

We define the update function ψ as follows, denoting the update probability of transition of a given cell from state a to state; b $P(a \rightarrow b)$, the list of its neighbours $\mathbf{n}$, the number of the neighbours having state 1 and i N_1 and N_i, respectively.

Assume that occupied patches can become vacant by local extinction (neighbour-independent property) or overcolonized by the other species. Hence

$$\psi(1, \mathbf{n}) = \begin{cases} 0 & P(1 \rightarrow 0) = e_1 \\ \mathbf{i} & P(1 \rightarrow \mathbf{i}) = (1 - e_1) r_{\mathbf{i}}(N_{\mathbf{i}}) \\ 1 & \text{otherwise} \end{cases} \tag{4}$$

$$\psi(\mathbf{i}, \mathbf{n}) = \begin{cases} 0 & P(\mathbf{i} \rightarrow 0) = e_{\mathbf{i}} \\ 1 & P(\mathbf{i} \rightarrow 1) = (1 - e_{\mathbf{i}}) r_1(N_1) \\ \mathbf{i} & \text{otherwise} \end{cases} \tag{5}$$

where e_1, e_i denote the species dependent extinction rates, and r_1, r_1 denote the overcolonization probability functions.

The fate of an empty patch is more complicated than occupied ones', because more neighbours can send colonizers (seeds) to there, and it must be somehow decided who wins such as in nature. The probability matrix of cases of colonization is shown in Figure 1, where $c_1 = c_1(N_1)$ and $c_i = c_i(N_i)$ denote the probabilities of colonization (seed dispersal) of a vacant cell by species 1 and i, respectively.

	i	
	c_i	$1-c_i$
c_1	? $0 \rightarrow 1, i$	$0 \rightarrow i$
$1-c_1$	$0 \rightarrow 1$	$0 \rightarrow 0$

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[4] This notation emphasizes the qualitative difference between the two species, like two units of complex plain

Figure 3. Colonization probabilities

If only species 1 colonizes the patch, which case has the probability of $c_1(1 - c_i)$, it will be occupied by itself.

If both species colonize the site (highlighted part in Figure 1), in order to select the winner we use seedling competition weight functions w_1 and w_i ($w_1 + w_i = 1$). In this case, the probability of successful colonization by 1 is $c_1 c_i w_1$. Colonization by i is symmetrical.

An empty site can remain empty if none of the species colonize it.

Hence, the corresponding update rules are:

$$\psi(0, \mathbf{n}) = \begin{cases} 0 & P(0 \to 0) = (1\text{-}c_1(N_1))(1\text{-}c_i(N_\mathbf{i})) \\ 1 & P(0 \to 1) = c_1(N_1)(1\text{-}c_i(N_\mathbf{i})) + c_1(N_1)c_i(N_\mathbf{i})w_1 \\ \mathbf{i} & P(0 \to \mathbf{i}) = c_i(N_\mathbf{i})(1\text{-}c_1(N_1)) + c_1(N_1)c_i(N_\mathbf{i})w_i \end{cases} \tag{6}$$

For simplicity assume that the seedling competition weights are of the form

$$w_1(\mathbf{n}) = \frac{c_1(N_1)}{c_1(N_1) + c_i(N_\mathbf{i})}, \quad w_i(\mathbf{n}) = \frac{c_i(N_\mathbf{i})}{c_1(N_1) + c_i(N_\mathbf{i})}, \tag{7}$$

if $c_1(N_1) + c_i(N_i) \neq 0$[5]. that means good colonizers (seed producers) are good competitors at the same time.

Overcolonization is a well investigated are of competition in the context of habitat destruction. Overcolonization facilitates coexistences both in spatially implicit and explicit models [Nee&May, Dytham] because it can compensate the higher colonization ability of other (weed-like) species. In a well balanced ecosystem weed-like species can fast colonize empty patches, but soon or later slower but more stable (superior competitor) species can overcolonize them. Habitat destruction brakes up this balance and superior competitor species go extinct [HEJ].

Non-indigenous fast spreading species have similar (or even higher) colonization ability than native weeds, but it can happen that superior competitors cannot overcolonize them.

The non-overcolonizing (zero) model, when both $r_1 \equiv r_i \equiv 0$ in (4) and (5) describes this case. In contradiction to the overcolonization model the zero-model

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[5] As $c_1, c_i \geq 0$, their sum can be zero only if they are both zero. In this case no colonization is possible.

proved to be much less robust to the initial patterns, initial occupation rate and the form of the colonization function [13]. It can be shown that soon or later one of the two competitors certainly dies out. From ecological point of view extended competition can considered as a practical coexistence. The length of this apparent coexistence (the expected lifetime of weaker species) proved to be highly dependent on explicit spatial patterns. To support this conjecture we ran a computer simulation series for a fixed parameter combination ($e_1 = 0.3$, $e_i = 0.1$, $c_1(N_1) = 0.1N_1$ and $c_i(N_i) = 0.04N_i$). Figure 4 shows the average time[6] of the weaker species' survivor in cases of starting from each possible chess-like and striped pattern can considered on a 128x128 cell space with 50-50 initial occupancies.
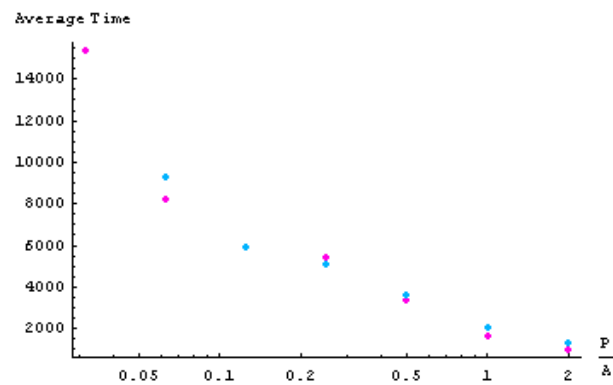

Figure 4. Average extinction time of the weaker species as a function of perimeter/area ratio in initial pattern configuration.

The difference between a 1 cell based chessboard pattern and a most aggregate initial pattern transcends two orders of magnitude.

Conclusions

Layers 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, particularly cellular automata for describing ecosystems.

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. If the native species are going to be displaced by the non-indigenous species is widely

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[6] Calculated from 250-250 runs.

influenced by the spatial pattern formation and the level of habitat destruction. In particular, random initial configurations that are generally assumed in biological modelling can give misleading results. It can be crucial in forecasting, since appropriate pattern formations can dramatically change the outcome of the competition or at least can slow down the extinction process of the weaker species such that the dynamics can be considered as practical coexistence.

Our experimental methods and tools can be applied for more general systems since they can be easily developed. For the investigations we developed program packages in *Mathematica*.

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