Artif Life Robotics (2002) 6:170–174

ORIGINAL ARTICLE

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A computational model of the interaction between environmental dynamics and economic behavior

Received and accepted: July 1, 2003

Abstract Environmental issues have been considered to be very important for a long time. We believe that they should be examined from an interdisciplinary view point in order to reach a solution, because they have arises as the consequence of complex interactions among various factors. This article proposes a new model termed *ColorChanger*. By using this model, we aim to explore the nature of ecological issues beyond separate discussions on specific subjects, and make the acquired knowledge available to encourage the solution of environmental issues. This article also reports on the results of the preliminary experiments.

Key words Cellular automata · Agent-based modeling · Ecology and economy · Environmental issues

1 Introduction

Environmental issues have been considered to be very important for a long time. They have been discussed in a wide range of fields from academic research to the international arena of politics. There are many academic fields in which environmental issues are tackled. However, there seems to be an essential problem with conventional approaches. For instance, there is a biological field termed conservation ecology, which investigates environmental issues. Conservation ecology belongs to ecological science, and aims at the conservation of biological diversity by conducting basic/applied research. Although the subjects of this approach range widely from genetic issues to landscape design, they rarely pay attention to the economic effects. On the other hand, environmental economics is a field in which environmental issues are discussed from an economic point of view. In environmental economics, the model of consumer and business behavior in traditional economics is evoked to explain who acts on the environment and why, and who suffers environmental damage and how. However, a consideration of the dynamics of life is rarely involved in these investigations. In the artificial society approach, which is a growing field, dynamic models are investigated where both environments as resources and economic behavior are considered. So far, however, most of them leave environmental variation out of consideration, although this must be very important when examining environmental issues in the real world from an interdisciplinary point of view.

Recently, Akiyama and Kaneko[1] constructed a computational model to focus on the interaction between the dynamics of the environment and agents' actions, and successfully analyzed the effects of this interaction on the dynamics of the environment and the evolution of agents' actions. Their study does not necessarily cope with environmental issues directly, but gives some indication that this type of constructive methodology could be very important when investigating the dynamics of the interactions between economic and ecological phenomena.

Encouraged by their results, we propose a computational model that makes it possible to discuss environmental issues from both an economic and a biological point of view. Our model consists of an economic activity model based on agent-based modeling, and a natural environment model based on cellular automata modeling. By conducting computational experiments, we focus on the interaction between economic activities and environmental variation based on the dynamics of an ecosystem surrounding human beings.

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This work was presented in part at the Sixth International Symposium on Artificial Life and Robotics, Tokyo, January 15–17, 2001

2 The model

2.1 Overview

There are several species of agents (players) and several game fields in *ColorChanger*. We denote a set of agent species as $S = \{1, 2, \ldots, s\}$ and a set of game fields as $G = \{1, 2, \ldots, g\}$. Each game field has a two-dimensional space that is marked off into $i \times i$ hexagonal cells, on which players repeatedly play some sort of economic games. Each cell has a "color" which expresses the state of its biological environment, and can be perceived by nearby players, including the agent who is on it. Each cell changes its color according to the color patterns on nearby cells like cellular automata. We define a set of players as $N = \{1, 2, \ldots, n\}$ in each game field. These n players are selected randomly from S. Each agent gets a reward by affecting its environment, in other words, by changing the color of the cell on which the agent resides. This is meant to be an economic action, and is decided based on a species-specific decision-making function (Fig. 1). An autonomous transition and a passive transition by the agent in the color of each cell constitute one round. Each game consists of T rounds, and games are played all at once in all game fields. Each agent acquires its profit in every round. Genetic operations are conducted after all games in g game fields are finished, as described in Subsect. 2.4. These procedures are conducted again and again.

2.2 Details of the game

The color density of the cells surrounding player i at time t is expressed as $e_i(t) = (e_i^{C(1)}(t), e_i^{C(2)}(t), \ldots, e_i^{C(c)}(t))$, where C is a set of colors on which cells can be laid. Each player has a state and a decision-making function. The state corresponds to the profit in the current round. Therefore the states and the decision-making functions of the agents are denoted by $y(t) = (y^1(t), y^2(t), \ldots, y^n(t))$ and $f = (f^{S(1)}, f^{S(2)}, \ldots, f^{S(n)})$, respectively, where the state of player i who belongs to species $S(i)$ at time t and the decision-making function of player i are denoted by $y_i(t)$ and $f^{S(i)}$, respectively. Player i decides its next action $a_i(t)$ based on $e_i(t)$ and $y(t)$. All of the players' actions are denoted by $a = (a^1(t), a^2(t), \ldots, a^n(t))$. Each player's individual actions can be either a "wait" (doing nothing) w, or changing the color of the cell on which the agent resides into one of the set of colors $D = \{m_1, m_2, \ldots, m_d\}(m_n \in C)$. The set of these feasible actions is denoted by $A = \{w, x^{m_1}, x^{m_2}, \ldots, x^{m_d}\}$, where x^{m_i} is the action of changing the color of a cell into color m_i. A and D are shared among all players, and are fixed throughout the generations.

The initial state of each player is assigned a random number generated from a normal distribution with a mean of 0.10 and a variance of 0.10 before the first round of the game. Each round consists of the following three steps: (1) environmental variation; (2) decision-making by players; (3) effects of actions on cell colors and allocation of profits to players.

(1) Environmental variation. This step consists of two steps. One is to change the colors of cells autonomously, and the other is to decrease the players' states to $y^i(t)' = u_N(y^i(t))$. We set $u_N(y) = 0.9y$ in this paper.

(2) Decision-making by players. Player i's decision-making function $f^{S(i)}$ decides its action $a^i(t)$ based on the states of the environment around that player, $e_i(t)$ (the den-

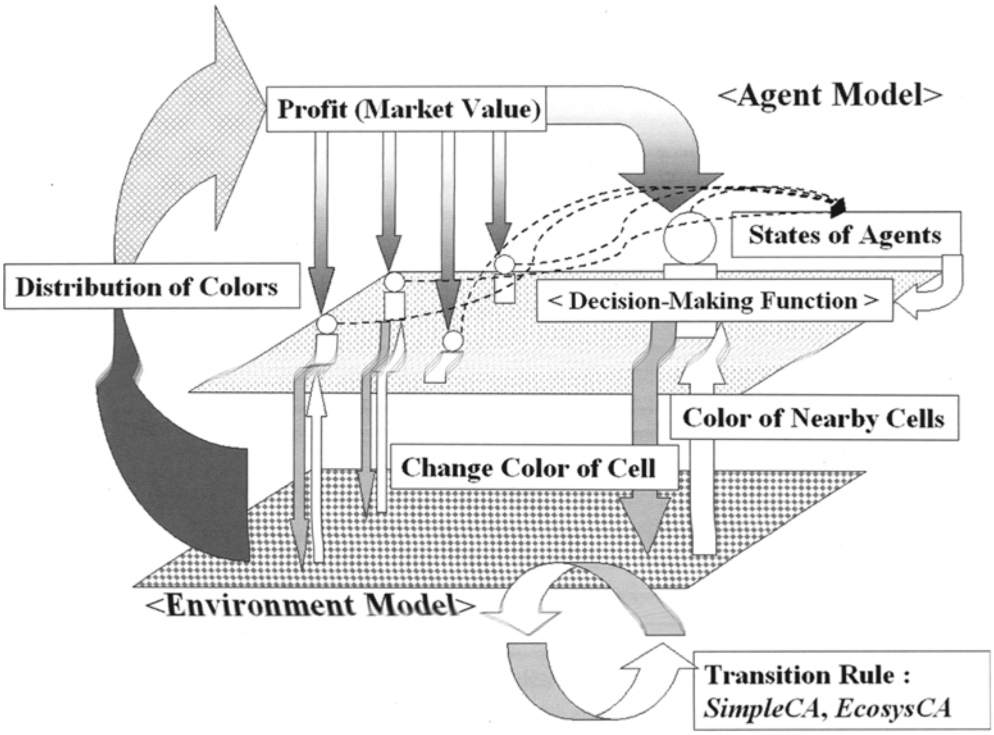


Fig. 1. Conceptual diagram of *ColorChanger*. The *upper plane* depicts the agent model, and the *lower plane* depicts the environment model. Mutual relations between the models are indicated by *arrows*

sity of the color in each neighboring cell), and the states of all players in its game field, $y(t)'$:

$$a^i(t) = f^{S(i)}\left(e^i(t), y(t)'\right) \tag{1}$$

where $f^{S(i)}$ is the inner structure of player i, and is invisible to other players, which could vary throughout its evolution.

(3) Effects of actions and allocation of profits. Each decision-making function of player i selects the largest motivation for feasible action in the motivation map[2] under the situation $\{e_i(t), y(t)'\}$ as follows:

$$\max\left(\{mtv_r\}\right): mtv_r = \eta_r e_i(t) + \sum_{l \in N} \theta_{lr} y^l(t)' + \xi_r \tag{2}$$

where mtv_r is the motivation for action $r (r \in A)$, $\{\eta_r\}$ is a $(d + 1) \times n$ real-number matrix, $\{\theta_r\}$ is a $(d + 1) \times c$ real-number matrix, and $\{\xi_r\}$ is a $(d + 1)$-dimensional real-number vector. Each element of $\{\eta_r\}$, $\{\theta_r\}$, and $\{\xi_r\}$ of the initial species of players is a set of random numbers generated from a normal distribution with a mean of 0.0 and a variance of 0.1. Players' actions decided in the previous step can change the colors of cells. The aggregate profit R is distributed to each action as $P = \{p^{D(1)}, p^{D(2)}, \ldots, p^{D(d)}\}$, based on the state distribution (at the time before the state change) calculated on randomly sampled cells as market values in reverse proportion to the frequency of the states. This method of profit distribution is based on the simple economic property that the rarer items have the higher values, and should make similar dynamics to the one in the so-called Minority Game.[3] Each $P^{D(i)}$ is equally divided among all players who chose action $D(i)$, which increases the states of the players. Then all players pay a cost Q.

2.3 Rules of color change and agent actions

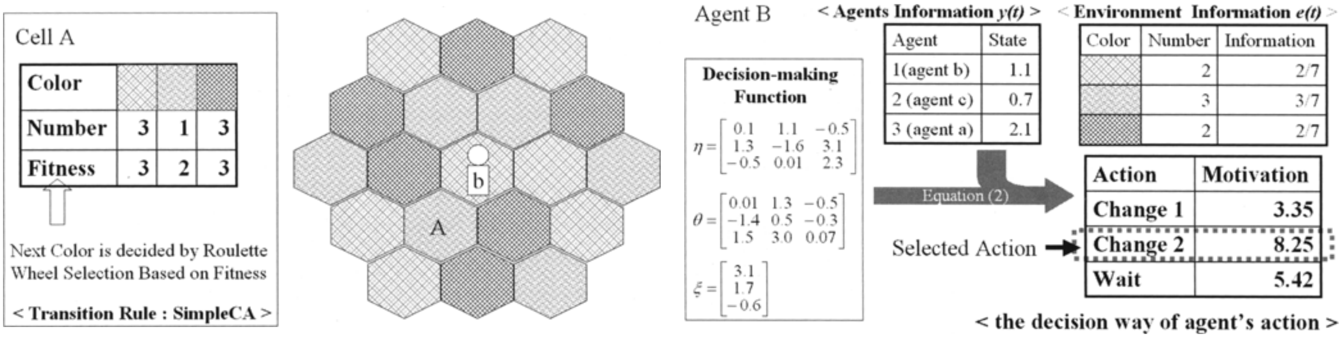
A set of the colors of cells is denoted by $C = \{1, 2, \ldots, c\}$, and each cell always takes one of these as a state. We adopt two types of rule by which cells change their color, *SimpleCA* (Fig. 2) and *EcosysCA*. The actions of players are also defined according to the adopted rule as follows.

(1) SimpleCA. The next color of each cell is decided by roulette-wheel selection based on the distribution of colors in the group of the six neighboring cells and itself. In counting each color, the number of its current color is multiplied by v in order to take account of an inertial effect concerning change of color. Agents are able to change the color of the cell on which they reside.

(2) EcosysCA. This rule expresses the dynamics of the ecosystem. The color of each cell represents the species of animate beings on it, and is denoted by $L = \{1, 2, \ldots, l\}$. An ecological food chain is predefined by links among the species based on the method by Williams and Martinez,[4] and the ecological niche can be organized under this rule. Not more than one animate being of each species can exist on each cell. In every time-step, every animate being on each cell executes one of the following actions: preys, bears a child, or moves. Prey is an action with a top priority, and is possible only when a prey exists on the same cell. The other two actions are conducted within six nearby cells. If there are no possible actions, the animate being stays on the same cell. These actions of animate beings change the colors of the cells. The color pattern on the plane of the game fields corresponds to the ecological niche. Two types of experiment concerning the players' actions are being conducted. One is that players directly affect the animate beings by hunting them and eliminating them from the cell. The players can affect d kinds of animate being randomly selected from L. The other experiment is that players do not deal directly with the animate beings, but change the colors of the cells on which they reside. A change of color by a player means that an animate being dies and/or is born. The players can change d kinds of color randomly selected from C, which contains 2^l colors that the cells can be laid on.

2.4 Evolution

Genetic operations are conducted on the agent species. The fitness of each agent species is calculated as the average profit of all agents that belong to the species during T rounds. The k species with the lowest k fitness are elimi-



Color	▨	▒	▓
Number	3	1	3
Fitness	3	2	3

$$\eta = \begin{bmatrix} 0.1 & 1.1 & -0.5 \\ 1.3 & -1.6 & 3.1 \\ -0.5 & 0.01 & 2.3 \end{bmatrix}$$

$$\theta = \begin{bmatrix} 0.01 & 1.3 & -0.5 \\ -1.4 & 0.5 & -0.3 \\ 1.5 & 3.0 & 0.07 \end{bmatrix}$$

$$\xi = \begin{bmatrix} 3.1 \\ 1.7 \\ -0.6 \end{bmatrix}$$

Agent	State
1(agent b)	1.1
2 (agent c)	0.7
3 (agent a)	2.1

Color	Number	Information
▨	2	2/7
▒	3	3/7
▓	2	2/7

Action	Motivation
Change 1	3.35
Change 2	8.25
Wait	5.42

Fig. 2. Details of the environmental model and the agent model with $n = 3$ (number of agents), $c = 3$ (number of colors which a cell can be laid on), $d = 2$ (number of colors to which agents change), $v = 2$ (coefficient of an inertial effect), and the *SimpleCA* rule. The *cental figure* expresses the situation at time t, the *left box* shows an example of color change on cell A, and the *right box* shows the decision-making by agent B

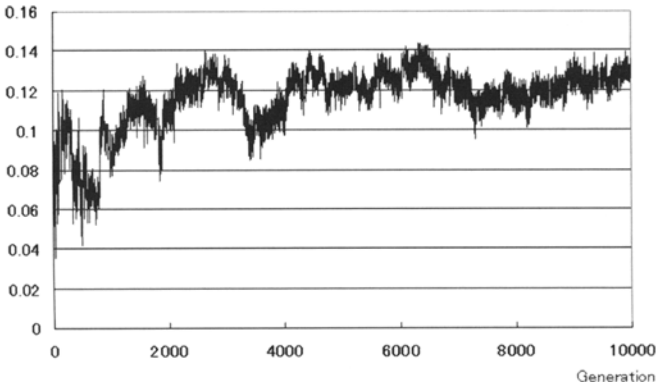


Fig. 3. Average fitness of agent species (in the *SimpleCA* model: $n = 3$, $c = 3$, $d = 3$, $I = 50$, $g = 60$, $T = 400$, $s = 10$, $k = 3$, $R = 1.5$, $v = 2$, $Q = 0.3$)

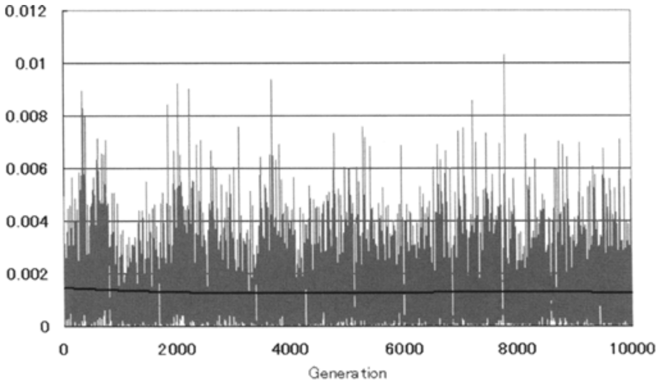


Fig. 4. The degree of divergence in color distribution with or without economic agents. The *gray line* shows the average divergence degree of colors, and *black line* shows the approximate curve

nated, and the surviving $s - k$ species leave their offspring with the same decision-making function for the next generation. The eliminated species are replaced by k new species. These are k mutant species randomly selected from surviving species. Mutation happens to every coefficient of the decision-making function of the parent species. Each coefficient in the decision-making function of a new mutant is chosen as a random number from the normal distribution, where the variance is 0.1 and the mean value is the corresponding element of $\{\eta\}$, $\{\theta\}$, and $\{\xi\}$ in the decision-making function of the parent species.

3 Preliminary experiments

SimpleCA was adopted as a transition rule in the preliminary experiments. The following parameters were used: c (number of cell colors) $= 3$, n (number of agents in each game field) $= 3$, and d (number of colors into which an agent can change) $= 3$. The environmental model was initialized with equal frequencies of each color in a random spatial distribution. Other parameters were set as follows: $i = 50$, $g = 60$, $T = 400$, $s = 10$, $k = 3$, $R = 1.5$, $v = 2$, and $Q = 0.3$.

Figure 3 shows a typical transition of the average fitness of agent species. The fitness of agents shows a tendency to increase smoothly. During the first 1000 generations, the agents' strategy (decision-making function) has no clear tendency, which generates a lot of "gambling" agents that behave in a hit-or-miss fashion. The strategy of the agents becomes relatively stable, without large oscillations, beyond about the 1000th generation. At the same time, the behavior of the agents also begins to change into the actions needed to obtain an assured income. The same strategy cannot always take a high fitness, because of the "noisy" situation in our model, including some sort of bounded rationality. On the other hand, there is a case where a good strategy continues to exist for a long time, and similar strategies are generated by mutation, which causes a decrease in the average fitness owing to a decrease in diversity. The "wait" action gradually disappears as the generation changes. The reason seems to be that it becomes more advantageous to do something, even though it is more risky than doing nothing.

Figure 4 shows the effect of the agents activities on the environment. The degree of divergence in color distribution with or without agents is measured as follows:

$$\frac{1}{c}\sum_{i\in C}\left(E_i - I_i\right)^2 \qquad (3)$$

where E_i is the actual existence rate of color i, and I_i is the ideal existence rate of color i. I_i is calculated as the average existence rate based on autonomous change in the environment without agents. In this case, when *SimpleCA* is adopted, the ideal average existence rates of all colors are the same because each color has the same probability of existence. This graph shows that the colors did not change much, although there are oscillations in each generation. There is no significant difference in the influence of agents on the environment throughout the generations. It is remarkable that the evolution of agents has so little effect on the environment, while it brings about a gradual increase in gains of agents.

4 Summary

ColorChanger is an attempt to investigate the interactions between the dynamics of the environment and the agents that influence the environment, in order to make it possible to discuss environmental issues from both an economic and a biological point of view. There are some noises which influence the dynamics in this model: the differences in the environmental information on all game fields, the environmental information obtained by agents, and information on the distribution of the colors used for the allocation of rewards. Based on preliminary experiments, we have shown that the agents could increase their fitness in spite of these factors. We conducted the experiments with an environmental model based on the dynamics of the ecosystem generated by the *EcosysCA* rule described in Sect. 2.3.

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