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Evolution of Adaptive Behavior toward Environmental Change in Multi-Agent Systems

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1. Introduction

An evolution-based approach to ecological modeling and simulation-based analysis of multiagent behaviors are important means to understand the origin and evolutionary process of a real creature. This is because a simulation enables us to experiment with a virtual world rapidly and repeatedly. However, a real creature is too complex to program on computers. This naturally demands that we grasp the essence of the real creature, simplify it, and program it as an agent (Todd & Wilson, 1993). In this approach, even if an agent that has only a simple mechanism initially, it can evolve and obtain complex behaviors through the process of evolution (Langton, 1986). This kind of synthetic method gives us a possible answer as to why or how the real creature obtains complex behaviors. Many studies have reported on the biology and behavior of real creatures with this approach. For example, from the aspect of animal behaviors, foodforaging (Koza et al., 1992) and herding (Oboshi et al., 2003; Werner & Dyer, 1993) are well-researched. Other examples are studies of specific creatures, such as egrets (Toquenaga et al., 1994), magicicadas (Marco Remondino, 2006), and the monarch butterfly (Hashizume et al., 2008; Sawada et al., 2002; 2004).

The monarch butterfly (*Danaus plexippus* L., *Nymphalidae*, *Lepidoptera*) is a good target for study. It has an interesting habit. The monarch butterfly is a migratory butterfly that requires three to five generations per annual migration. We will describe its habit in detail below (The University of Kansas Entomology Program, 2008).

The monarch butterfly mainly lives in North and Central America. As winter ends and spring begins, spring populations of the monarch butterfly in Mexico prepare for migration. And they start to migrate north. The migrating females lay eggs and repeat alternation of generations. In the beginning of summer, they reach the southern part of Canada. Fall populations which are born at the beginning of fall are known to be biologically and behaviorally different from spring populations. Temperature and day length influence their eggs. Fall populations migrate south back to Mexico only one generation. This travel is more than 3500 km. But it takes them only 75 days to travel using air current. It means that the butterfly flies 50 km per day. They return to Mexico again in a single generation. And the monarch butterfly repeats their migration.

The butterfly migrates as described, and its migration is different from that of a bird. We stated before that the monarch butterfly requires three to five generations per annual migration. This means that the migration cannot be taught by parents. Stated differently, genes teach the migration to the butterfly. Many researches and experiments (Alerstam et al., 2003; Etheredge et al., 1999; Perez et al., 1997; Schmidt-Koenig, 1985; Walker, 2001) have been

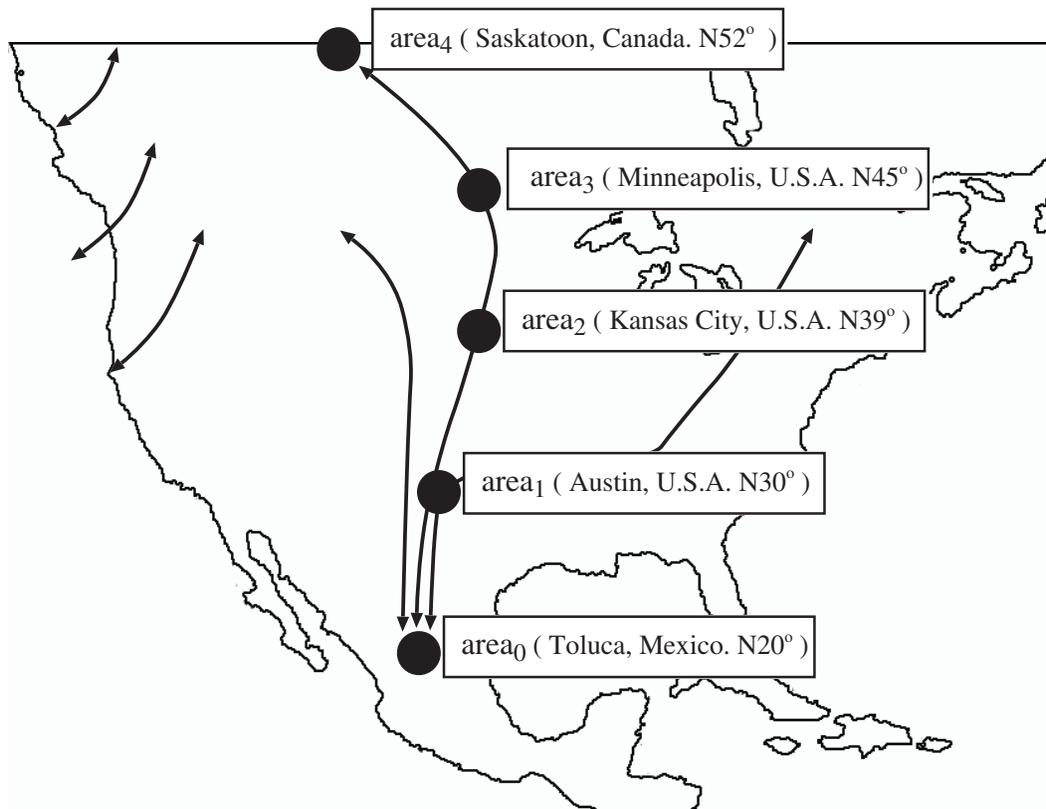


Fig. 1. Spring and fall migrations of the monarch butterfly in North and Central America (revised, from (Brower & Malcolm, 1991)), and 5 areas model

conducted on the proximate factors why the monarch butterfly migrates, and we know that the butterfly migrates by the combination of all the different physiological functions. However, evolutionary factors of its migration have yet to be determined. In other words, we do not know the catalyst for the monarch butterfly to start migration, and it has not been clear what processes the butterfly has gone through until it acquired the current migration style. For answering the question, we frame the hypothesis that environmental change of temperature is a trigger for the butterfly to acquire the migration behavior. It is believed that one of the selection pressures that has driven this species' evolution was the gradual rise in air temperature after the ice age. A non-migratory butterfly had slowly evolved and adapted to the environmental changes and then became a migratory butterfly over time.

In this paper, we model areas from the habitat where the monarch butterfly lives, and design agents based on the monarch butterfly. The agent has genes expressing both physical features and action decision ability. This paper attempts to investigate what adaptive behaviors the agents obtain under the dynamic environment and to assess the validity the model to compare the agent's behavior with the monarch butterfly's behavior.

The paper is organized as follows. Second section gives a definition of the ecosystem consisting of areas, plants, and agents. Third section executes the simulation using the eco-system and describes our observation about the result. Fourth section concludes the paper and lastly gives future extensions.

2. Ecosystem

The ecosystem we designed consists of areas, plants, and agents. Each agent conducts one action per area per day, which we define as unit time. We define one year as a number of fixed days, *DAY*.

2.1 Area

2.1.1 Definition

An area consists of a two-dimensional 50×50 grid of square locations. The ecosystem has five areas. Five areas are $area_0, area_1, \dots, area_4$, located south to north modeled after North and Central America (Fig. 1).

The area has plants, agents, and temperature as an environmental parameter. We express $area_i$ (i : identifier) as

$$area_i(Agent_i, Plant_i, tmpr_i). \quad (1)$$

$Agent_i$ is a set of agents, $Plant_i$ is a set of plants (we will describe the agents and plants later), and $tmpr_i$ is the temperature.

2.1.2 Seasonal temperature change

The temperature, $tmpr_i$, changes periodically for short-term like seasonal change. We call it short-term change. For a short-term change, we use real temperature data from Central and North America. Figure 1 shows the real temperature data, but it is an average of the monthly data. We wanted averaged daily data, so we approximated the real temperature data into an approximate average daily data using a sin function (Figure 2). The temperature: $tmpr_i(d)$ in $area_i$ for day d is determined by

$$tmpr_i(d) = \alpha_i \sin(2\pi d / DAY) + \beta_i, \quad (2)$$

where α_i and β_i are constant numbers in each area.

2.1.3 Air current

The ecosystem has an air current from $area_4$ to $area_0$. The air current helps the agent which moves in the same direction¹. Hence, if the agent starts migration south from $area_1, area_2, area_3$, or $area_4$, the agent can directory land on $area_0$ (we will see the agent and its actions later).

2.2 Plant

2.2.1 Definition

A plant p_j (j : identifier) is expressed by

$$p_j(age_j), \quad (3)$$

where age_j is the number of days for which the plant has existed. The plant is the energy source for the agent.

¹ Fall populations of the monarch butterfly are said to glide and be carried by an air current during fall migrations(Gibo & Pallett, 1979).

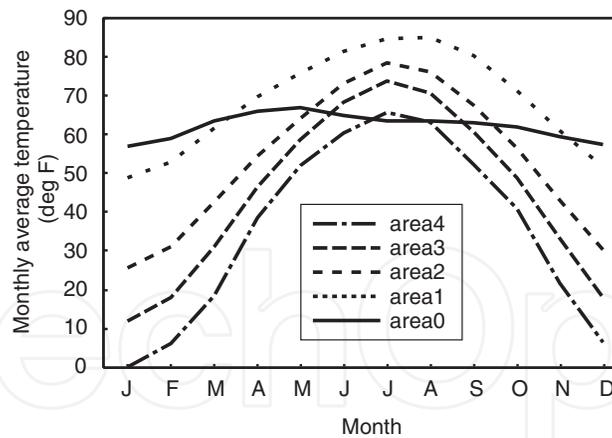


Fig. 2. Real temperature data (National Oceanic and Atmospheric Administration, 2008).

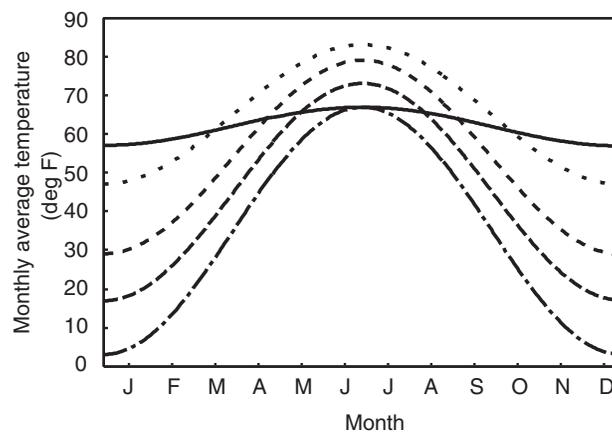


Fig. 3. Approximate temperature data.

2.2.2 Appearance & Disappearance

The birth number of plants: N_i^{plant} in $area_i$ is determined by

$$N_i^{plant} = M_i^{plant} \times (1 - \Delta_{suit_tmpr}^{plant} / S_t), \quad (4)$$

$$\Delta_{suit_tmpr}^{plant} = |tmpr_i(d) - suit_tmpr^{plant}|, \quad (5)$$

where M_i^{plant} is the maximum birth number of plants in $area_i$ in one day, S_t is a constant, and $suit_tmpr^{plant}$ is the most suitable temperature for the plant. As you know from Eq 4, the temperature in the focused area determines the birth number of plants. In our simulation the upper limit of the birth number in each area is different. The birth number in $area_0$ is smaller than the others². After the birth number is determined, each plant is set in a random grid.

² It is because the shortage of food or milkweed in the southern area is thought to have caused the migration of the Monarch butterfly.

If the plant suffers either of the following conditions, it is removed from the simulation. T_d^{plant} is the maximum lifetime of plants.

$$\text{“An agent eats the plant”} \quad \text{or} \quad age_j > T_d^{plant} \quad (6)$$

2.3 Agent

2.3.1 Definition

Agent a_j (j is identifier) is expressed by

$$a_j((ea_j, st_table_j), (age_j, in_j)), \quad (7)$$

where ea_j is the environmental adaptation scale, st_table_j is the action decision table, age_j is the number of days the agent has existed, and in_j is the energy level.

The first two elements, ea_j and st_table_j , are inherited. It should be noted that ea_j and st_table_j are encoded into different genes. However, the last two elements, age_j and in_j , are not inherited. age_j and in_j are initialized when the agent is born.

2.3.2 Environmental adaptation scale

The environmental adaptation scale (EA), ea_j is an integer fulfilling $0 \leq ea_j \leq M_{ea}$ where M_{ea} is the maximum number of EA. ea_j is calculated by

$$ea_j = \text{count}(\text{bitset}_{ea_j}), \quad (8)$$

where bitset_{ea_j} is an array of bits representing the EA, and count is the function that returns the number of bits that are set to 1 in the array. We use the EA to represent the physical features of the agent, for example, “thickness of the exoskeleton.” In other words, if the EA is large, it means that the agent can stand a large temperature variation, and it also means that the agent is heavy and spends a lot of energy for actions. If the EA is small, it conversely means that the agent cannot stand a large temperature variation and nevertheless the agent is light.

We use the EA to implement for the agent a sensory system that enables it to feel temperature.

2.3.3 Sense

Agent, a_j , senses the information shown in Table 1. The information is about the internal information of its own energy level, in_j , and about external information, ex_j . The internal information is on whether the agent has the energy level in the condition of “ $in_j > I_e$.” I_e is a certain energy level. The external information is on “finding plants?”, “finding other agents?”, and “how does the agent feel about the temperature?”

To sense all of this information, the agent has visibility around constant grids to find other agents and plants and has a temperature sensor. Therefore, the agent can feel whether $tmpr$ is “hot,” “cold,” or “suitable.” To implement this sensor, the agent has a range of temperatures named $suit_tmpr_j$ ³ given by

$$S_b - K_s \times \frac{ea_j}{M_{ea}} \leq suit_tmpr_j \leq S_b + K_s \times \frac{ea_j}{M_{ea}}, \quad (9)$$

where S_b and K_s are constant values to construct $suit_tmpr_j$. If $tmpr$ is within the range of $suit_tmpr_j$, the agent feels the area is “Suitable.” If $tmpr$ exceeds the maximum temperature

³ $suit_tmpr_j$ takes the value within a certain finite range because ea_j is also finite. Therefore, the agent cannot have a perfect $suit_tmpr_j$ that covers all temperatures.

of $suit_tmpr_j$, it feels the area is "Hot." Also, if $tmpr$ is below the minimum temperature of $suit_tmpr_j$, it feels the area is "Cold."

2.3.4 Action

Five actions ($\in ACT$: Table 2): "eat", "reproduce", "migrate north", "migrate south", and "do-nothing" can be performed by the agent. We explain them below.

The first action is "eat." The agent can eat a plant to absorb energy if the agent is next to the plant. Otherwise, if the agent finds a plant within its range of vision, it moves toward the plant. We categorize this action as "eat." Incidentally, if the agent cannot find any plants, the agent changes the action from "eat" to "do-nothing" (we will see "do-nothing" later.).

The second action is "reproduce." The agent can make an offspring if it is next to another agent (we will also see the reproduction process later.). Otherwise, if the agent finds another agent within its range of vision, the agent moves toward it. We categorize this action as "reproduce." If the agent cannot find any agents, the agent changes the action from "reproduce" to "do-nothing."

The third action is "migrate north." When the agent selects the "migrate north" action, the agent migrates to the northern areas. If the agent is in $area_i$, it migrates to $area_{i+1}$. Note that the agent in $area_4$ cannot migrate northward. Hence, in this case the agent changes the action from "migrate north" to "do-nothing."

The fourth action is "migrate south." "migrate south" is almost the same as "migrate north" except for the direction. When the agent selects the "migrate south" action, the agent migrates to the southern areas. If the agent is in $area_i$, it migrates to $area_0$. Note that the agent in $area_0$ cannot migrate southward. The action is changed from "migrate south" to "do-nothing."

The fifth action is "do-nothing." The agent which selects "do-nothing" does not move and stays the same grid for one day. We allow the agent to select "do-nothing." In addition to this, if the agent fails in the previous four actions, the agent must perform "do-nothing."

Info	Statement	Decision
in_j	Enough energy?	$X_0 = \text{Yes/No}$
ex_j	Find plants?	$X_1 = \text{Yes/No}$
	Find other agents?	$X_2 = \text{Yes/No}$
	Temperature?	$X_3 = \text{Hot/Cold/Suitable}$

Table 1. Sensory information.

Action	(Abbr.)	Detail
eat	(E)	Eat a plant or approach it
reproduce	(R)	Reproduce a new agent or approach another agent
migrate north	(Mn)	Migrate to northern area
migrate south	(Ms)	Migrate to southern area
do-nothing	(N)	Do not move

Table 2. A set of ACT .

2.3.5 Action decision table

The agent, a_j , decides which action, act , performs by

$$act = st_table_j(X_0, X_1, X_2, X_3), \quad (10)$$

where st_table_j is the action decision table, and $X_$ is a sensory information. st_table_j combines a condition alternative table with an action table. The former table is a common table for all agents and it has 24 columns. Conversely, each agent does not have the same action table, because the table is expressed by gene. st_table_j has four entries. As you see from Table 1, $X_$ has a decision for each statement. A set of $X_$ determines agent’s action. Table 3 provides a concrete example of the action decision table.

		1	2	3	4	5	...	24
Sensory Information	X_0	Y	Y	Y	Y	Y	...	N
	X_1	Y	Y	Y	Y	Y	...	N
	X_2	Y	Y	Y	N	N	...	N
	X_3	H	C	S	H	C	...	S
Actions	E				√		...	
	R			√			...	
	Mn	√					...	
	Ms		√				...	
	N					√	...	√

Table 3. An example of action decision table. The agent performs a checked action corresponding with a set of alternatives of sensory information. Key: Y=Yes, N=No, H=Hot, C=Cold, S=Suitable.

2.3.6 Energy level update

After the action, the energy level is updated by

$$in_j \leftarrow in_j + f(act, ea_j, suit_diff), \tag{11}$$

where function f is the update function of the energy level. $suit_diff$ is the difference in temperature between $tmpr$ and the edge of $suit_tmpr_j$ is given by

$$suit_diff = \begin{cases} tmpr - \max(suit_tmpr_j), & \text{“Hot”} \\ \min(suit_tmpr_j) - tmpr, & \text{“Cold”} , \\ 0, & \text{“Suitable”} \end{cases} \tag{12}$$

where function \max returns the maximum temperature within the range of $suit_tmpr_j$, and function \min returns the minimum temperature within the range of $suit_tmpr_j$. If the agent with ea_j performs act in the condition of $suit_diff$, the function outputs the amount of change in the energy level. We later explain in detail which action increases and decreases the energy level.

We categorize the actions into three groups according to the way of decreasing the energy, (a) decreasing in a certain amount of energy: “reproduce” provided that the agent succeeds in making its offspring, (b) decreasing in proportion to ea_j : “migrate north/south”, and (c) decreasing in proportion to $suit_diff$: moving by “eat”, moving by “reproduce”, or “do-nothing” actions.

However, the only one action that the agent can actually increase its energy level is to perform “eat” action when it encounters a plant.

Symbol	Value	Description
$DAY(1year)$	300	Number of days of 1 year.
SW	10	Amplitude of the temperature caused by short-term change.
$av_tmpr_i(0)$	10,20,30,40,50	Average yearly temperature in year 0.
M_{ea}	30	Maximum number of EA.
I_e	100	Threshold in which an agent senses it has enough energy.
S_b	50	Constant value to construct $suit_tmpr_j$.
K_s	15	Constant value to determine the width of $suit_tmpr_j$.
I_f	100	Energy level which a newborn agent has.
T_D	100	Agent's maximum lifetime.

Table 4. Parameters Setting.

2.3.7 Reproduction

Two agents, a_{p1} , a_{p2} , reproduce and leave offspring agent, a_j , with

$$a_j((ea_j, st_table_j), (age_j, in_j)), \quad (13)$$

$$ea_j = mu_{ea}(cr_{ea}(ea_{p1}, ea_{p2})),$$

$$st_table_j = mu_{st}(cr_{st}(st_table_{p1}, st_table_{p2})),$$

$$age_j = 0,$$

$$in_j = I_f,$$

where cr_{ea} and cr_{st} are the crossover functions for $ea_$ and $st_table_$, respectively. mu_{ea} and mu_{st} are the mutation functions for $ea_$ and $st_table_$, respectively. Note that age_j is initialized by 0, and that in_j is also initialized by I_f which is the initial energy level.

We detail each function. cr_{ea} is the function which cross over parent agent's environmental adaptation scales. This function performs uniform crossover for $bitset_{ea}$. Meanwhile, cr_{st} performs one-point crossover for action table. mu_{ea} and mu_{st} give mutation to each element to increase biological diversity. mu_{ea} makes one of the bits in $bitset_{ea}$ flipped. mu_{st} changes one of the columns into the others.

2.3.8 Death

If the agent suffers either of the following conditions, it dies and is removed from the simulation.

$$in_j < 0, \quad (14)$$

$$age_j > T_D, \quad (15)$$

where T_D is the maximum lifetime. The first condition is "starvation," and the second is "death because of old age."

3. Experiment

In this section, we present the details of an experiment carried out using our defined ecosystem. The purpose of this experiment is to observe how the agents evolve and what adaptive behaviors the agents obtain in an environment that has short-term change and is locally bias of food distribution. The parameter setting is listed in Table 4.

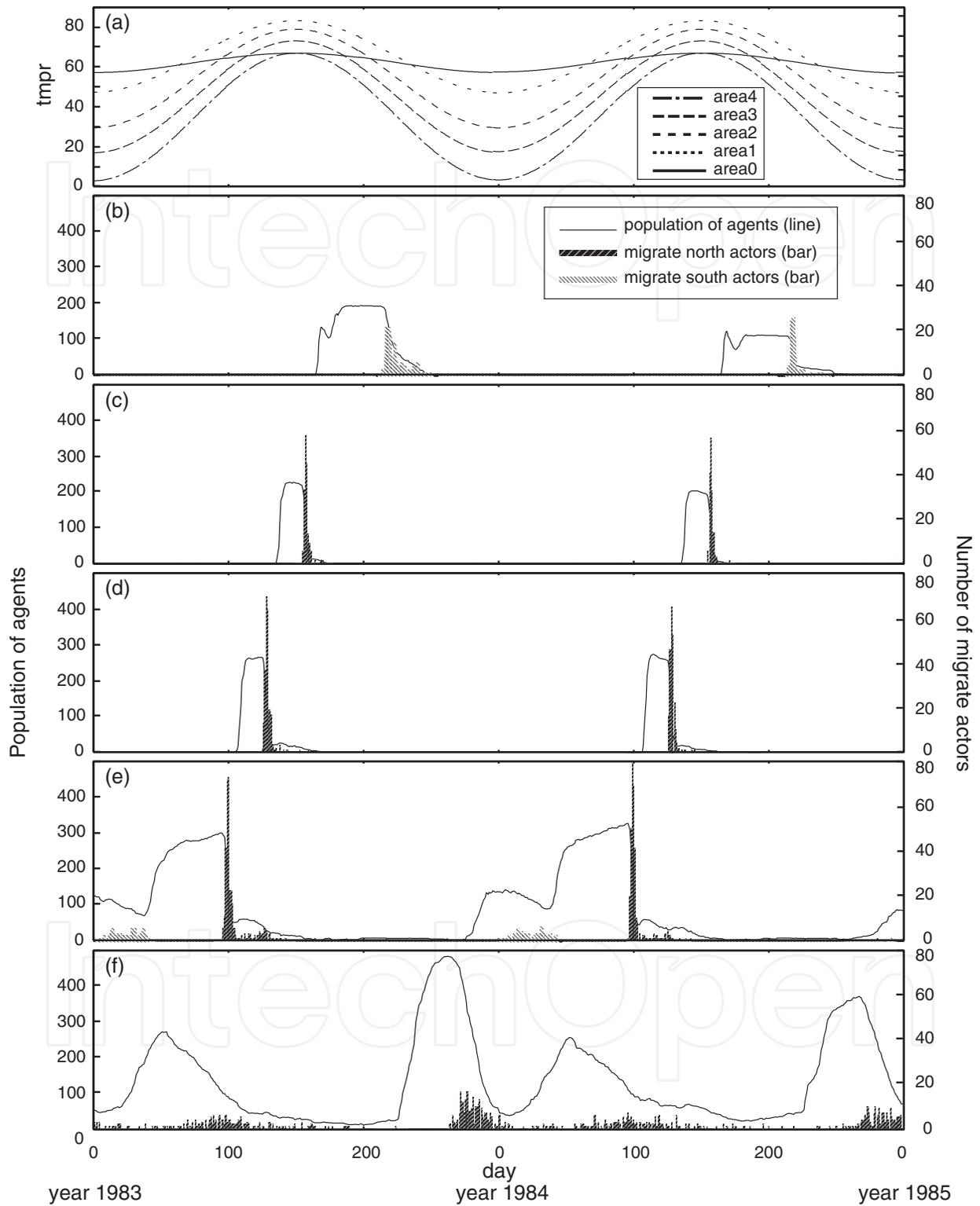


Fig. 4. (a) Temperature for 2 years. (b) Population of agents and number of migrate actors which behave “migrate north/south” in $area_4$. (c) is in $area_3$. (d) is in $area_2$. (e) is in $area_1$. (f) is in $area_0$.

The results are shown in Figure 4. We executed a simulation using our defined ecosystem for a period of 2000 years. It is difficult to describe all the results for the entire period. So in Figure 4, we extracted 2 years from the 2000 years, and now are providing a detailed analysis. Figures 4(b)-(f) show the population changes and the number of migrate actors. As is evident from these figures, the agents obtained three emergent behaviors and adapted to the environment.

3.1 Stay in $area_0$

Figure 4(f) shows that some agents stayed in $area_0$ throughout the year. This means that a certain number of agents did not move to other areas, but remained in $area_0$. From the aspect of temperature, $area_0$ is the most suitable area. However, $area_0$ had a food shortage problem. So, other behaviors were observed.

3.2 Migration between $area_0$ and $area_1$

We focus on Figures 4(e) and (f) in this subsection. We confirmed the agents moved to $area_1$ from $area_0$ by selecting the “migrate north” action between year 1983 day 260 and year 1984 day 10. Then, between year 1984 day 0 and year 1984 day 40, some agents selected and executed a “migrate south” action and went back to $area_0$. These agents migrated between $area_0$ and $area_1$ for only 40-80 days. We can easily assume one reason for the agents to behave like this, a food shortage problem in $area_0$. Around year 1983 day 270, $area_0$ held the biggest number of agents. This caused a food shortage. The number of plants in $area_0$ decreased to 9 (in this 2 year period, the maximum number of plants in $area_0$ was 93.). When $area_0$ reached this condition, the agents selected to go to $area_1$. Stated another way, the action decision table of the agents evolved to selecting “migrate north” when the agent could not find any plants. However, it was not necessarily the best behavior from the aspect of temperature. The movement north around year 1983 day 260 - year 1984 day 10 meant that the agent left the most suitable area based on temperature. $area_1$ was a little colder at this time. Therefore, the agents soon returned to $area_0$.

3.3 Migration between $area_0$ and $area_4$

As in Figures 4(b) - (f), this migration behavior can be confirmed. First, we talk about the northward migration. A small number of the agents moved to $area_1$ from $area_0$ between year 1983 day 260 and year 1984 day 10. The number of agents in $area_1$ increased and around year 1984 day 100 moved to $area_2$. Moving to $area_3$ from $area_2$ was around year 1984 day 130, and moving to $area_4$ from $area_3$ was around year 1984 day 160. The agents stayed in $area_4$ for 60 days and then started back to $area_0$. This was around year 1984 day 220. As stated above, the agents established a migration behavior between $area_0$ and $area_4$. The reason why the agents migrated over the areas is attributed to the agents’ adaptation to both short-term change and a food shortage.

3.4 Patterns of cross-generational migration

We have other results that helped us determine when the migration began and how many agents migrated. Before showing these results we will define the four migration behaviors that our ecosystem can achieve: migration between $area_0$ and $area_1$, migration between $area_0$ and $area_2$, migration between $area_0$ and $area_3$, and migration between $area_0$ and $area_4$. Figure 5 presents the results. It shows the development of migratory agents for a 2000 year period. Each migratory agent increased year by year. At the end of the experiment, all migration behaviors became apparent. Fig. 6 shows the more detail description of migration between $area_0$ and $area_3$ and between $area_0$ and $area_4$ in year 2000. We add some analysis to the

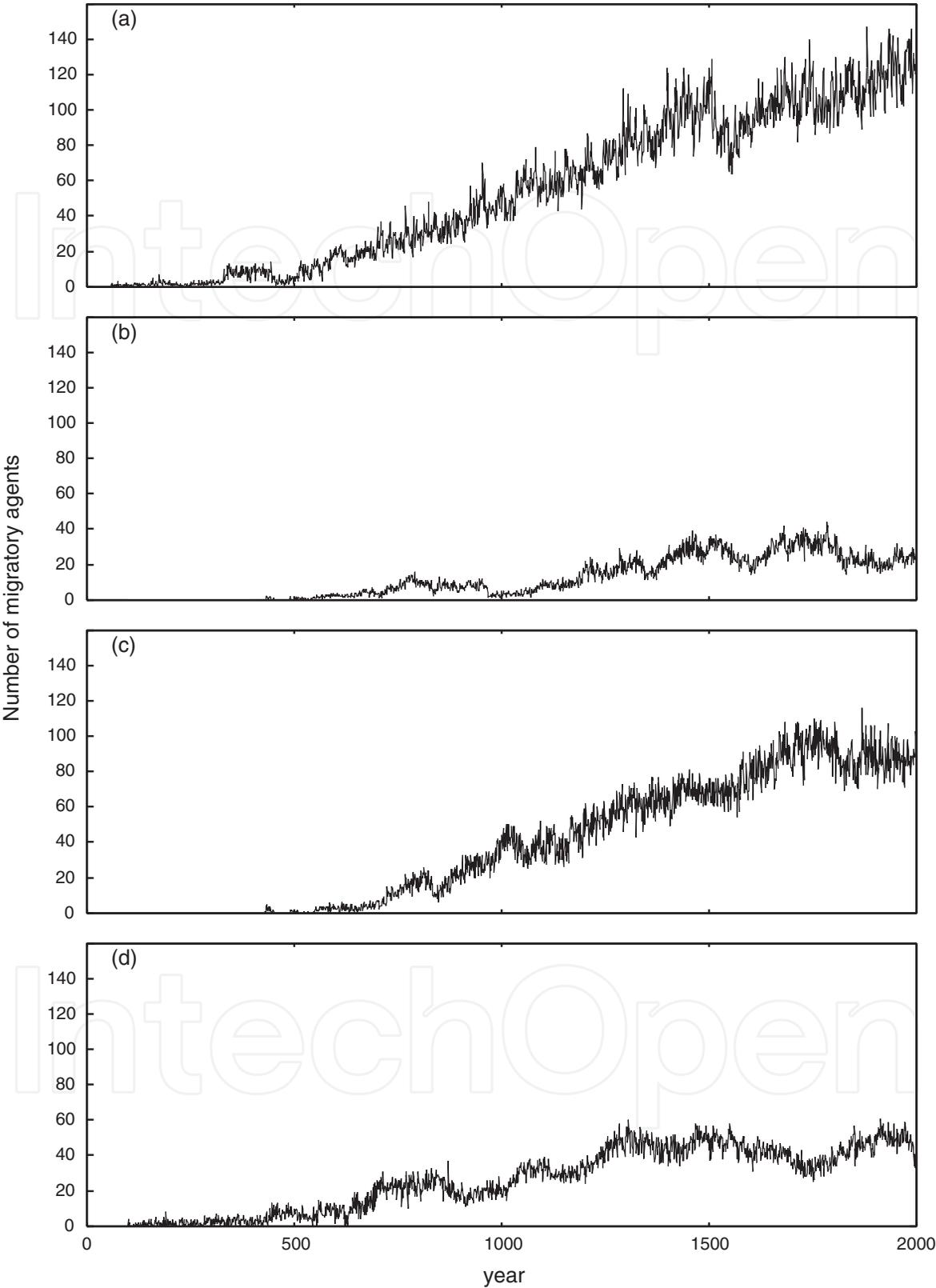


Fig. 5. (a) Number of migratory agents between $area_0$ and $area_1$. (b) is between $area_0$ and $area_2$, (c) is between $area_0$ and $area_3$, (d) is between $area_0$ and $area_4$. All points are average of 50 trials.

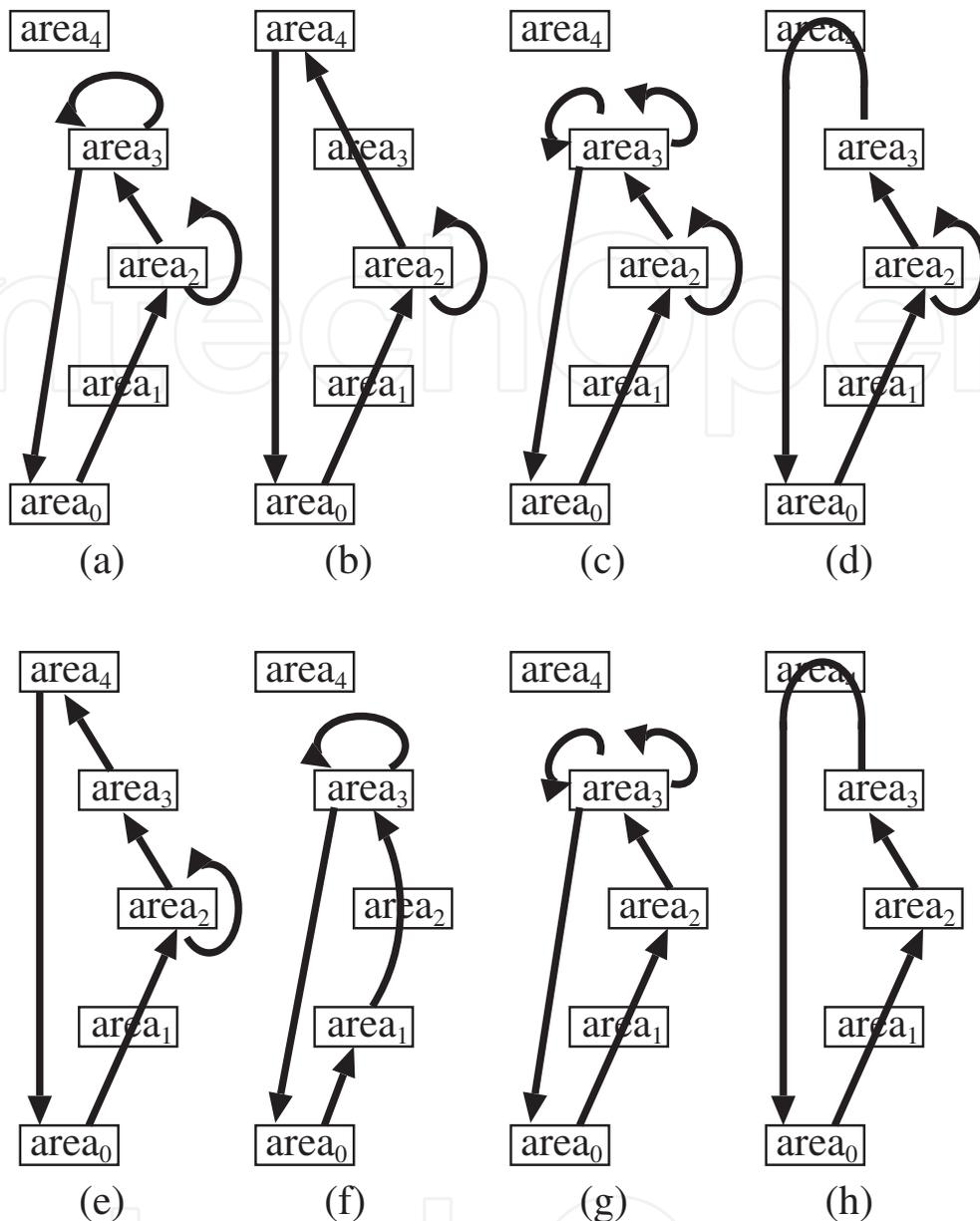


Fig. 6. Patterns of cross-generational migration in year 2000. One arrow is the length that one agent moves for its life. For example, migration of (a) takes five generations per annual migration. Each percentage of total is followings: (a) 25.8%, (b) 14.9%, (c) 11.6%, (d) 11.5%, (e) 8.4%, (f) 6.0%, (g) 5.0%, and (h) 4.0%.

figure. From the figure, we can understand how far one agent moved and where the agent reproduced. One line is the route which the agent moved for its life. We focus on Fig. 6 (a) as an instance. This migration took 5 generations per annual migration. The first generation was born in $area_0$ and it moved to $area_2$ through $area_1$ and then this generation made its offspring in $area_2$. The second generation did not move over areas but stayed in $area_2$ and it made the third generation. The third generation left for $area_3$ and made the fourth generation. The fourth generation stayed in $area_3$. The fifth generation moved back to $area_0$ from $area_3$. This is the detail analysis for Fig. 6 (a). And we focus on the common phenomenon in Fig. 6. The behavior until the second generation was quite same. The first generation moved to $area_2$

from $area_0$ through $area_1$ and the second generation stayed in $area_2$ and it made offspring there. The possible reason of this phenomenon is the temperature in $area_0$ and $area_1$. At this time (year 2000), the temperature in $area_0$ and $area_1$ were so high that it was not suitable for many agents to behave “reproduce” action because it needed a lot of energy. So many agents moved to $area_2$ at a first move and executed “reproduce” action.

It is difficult for us to compare the result with the monarch butterfly’s migration. Because no one knows the precise migration patterns when and where the monarch butterfly alternates its generation. However, from the aspect which the monarch butterfly takes some generations per annual migration, the simulation gave us the same emergent behaviors.

4. Conclusion

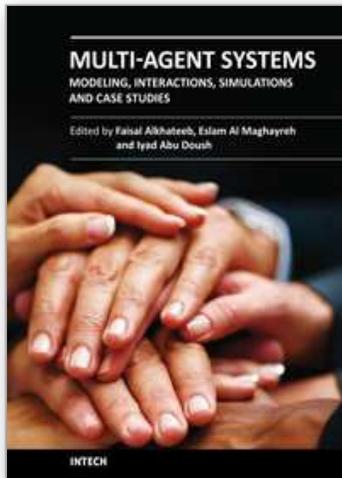
In this paper, an artificial ecosystem for migratory agents was described. Firstly, we constructed an ecosystem consisting of five areas, plants and agents. Each area has two kinds of dynamic changes in temperatures: long-term and short-term changes. Each agent living in the area has two genetic components: an environmental adaptation scale and an action decision table. The environmental adaptation scale enables the agents to have a temperature sensor. Secondly, we conducted the experiment with this ecosystem. The result showed that the agents obtained migration behavior similar to that of the monarch butterfly.

In this paper, it is particularly worth noting that we tried to realize a real creature on the computer with as simple mechanisms as possible. On the environment we focused on only temperature from an endless number of environmental parameters. Also on the monarch butterfly, we focused on only two elements from various kinds of parameters such as physical features, sensors, and so on. This policy relates to the policy which we stated in introduction. For future works, firstly, the research is needed additional experiment. We confirmed that the agents acquired migration behavior under our proposed model. To construct the model, we defined four elements: short-term change and long-term change for dynamic environment, and environmental adaptation scale and action decision table for agents. We need additional experiment to understand which elements are indispensable. Secondly, we need more rigorous evaluation of the stability of migration behavior. In case of many times migrations by one agent, we can determine that the agent behaves stably and adaptively to the environment. However, if the migration takes some generations like our simulation, we cannot clearly state whether the agents are always stable. Lotka-Volterra (Lotka, 1925; Volterra, 1928) equation modeling the relationship between predator and prey is famous and it can provide rigorous evaluation of balance of the relationship. Our model and results of experiment also need this kind of mathematical evaluation.

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