Physica A 490 (2018) 803–807

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Cellular automaton for migration in ecosystem: Application of traffic model to a predator–prey system

Takashi Nagatani [a,*], Kei-ichi Tainaka [b]

[a] Department of Mechanical Engineering, Shizuoka University, Hamamatsu, 432-8561, Japan
[b] Graduate School of Science and Technology, Shizuoka University, Hamamatsu, 432-8561, Japan

HIGHLIGHTS

- We applied the traffic model to a predator–prey system.
- We presented a cellular automaton model for migration in ecosystem.
- We studied the effect of migration on populations of preys and predators.
- We explored that the migration of predators induces a self-organized pattern.

ARTICLE INFO

Article history:
Received 18 March 2017
Received in revised form 1 June 2017

Keywords:
Lotka–Volterra model
Traffic model
Migration
Cellular automaton
Prey–predator system
Self-organization

ABSTRACT

In most cases, physicists have studied the migration of biospecies by the use of random walk. In the present article, we apply cellular automaton of traffic model. For simplicity, we deal with an ecosystem contains a prey and predator, and use one-dimensional lattice with two layers. Preys stay on the first layer, but predators uni-directionally move on the second layer. The spatial and temporal evolution is numerically explored. It is shown that the migration has the important effect on populations of both prey and predator. Without migration, the phase transition between a prey-phase and coexisting-phase occurs. In contrast, the phase transition disappears by migration. This is because predator can survive due to migration. We find another phase transition for spatial distribution: in one phase, prey and predator form a stripe pattern of condensation and rarefaction, while in the other phase, they uniformly distribute. The self-organized stripe may be similar to the migration patterns in real ecosystems.

1. Introduction

Ecological system has been investigated intensively [1–6]. Population dynamics such as predator–prey system has been studied from various points of view. Migration effect in ecosystem has attracted much attention [7–10]. From a physical point of view, the migration has been mainly modeled as a diffusion process. Sometimes predators move around like a diffusion process. On the other hand, they sometimes go forward over a long distance [10]. Here, we apply a traffic model to explore the effect of such a directional motion.

Recently, traffic and pedestrian flows has attracted much attention among physicists [11–38]. Various models have been presented to understand the rich variety of physical phenomena. The traffic models are suitable to study not only dynamics of vehicles but also the directional motion of animals. The traffic models can be applied to the migration process of animals.

* Corresponding author.
E-mail address: tmtnaga@ipc.shizuoka.ac.jp (T. Nagatani).

http://dx.doi.org/10.1016/j.physa.2017.08.151
0378-4371/

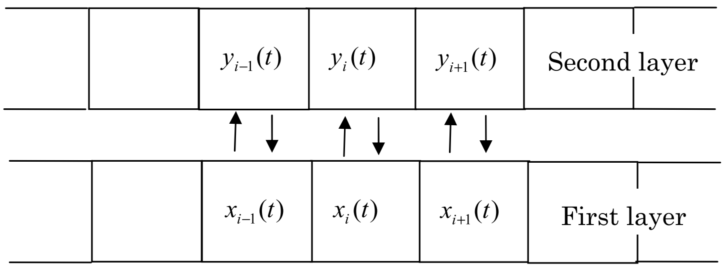

Fig. 1. Predator-prey system on one-dimensional lattice with two layers. There exist preys (grass) only on the first layer and predators (animals) only on the second layer. Predators on the second layer interact with preys on the first layer. The states of preys and predators at time t are represented by $x_i(t)$ and $y_i(t)$. Each lattice site on the first layer is X (prey) or O (empty). Each lattice site on the second layer is Y (predator) or O (empty).

A typical case of lattice Lotka–Volterra model has been studied by many authors. In particular, we focus on the following model [39–43]:

$$X + Y \to 2Y \tag{1a}$$

$$X + O \to 2X \tag{1b}$$

$$Y \to O. \tag{1c}$$

This system contains prey (X) and predator (Y); the symbol O means empty. The process (1a), (1b) and (1c) denote the predation of Y, reproduction of X and the death of Y. Both species X and Y cannot coexist on one-dimensional (1-d) lattice, but they can coexist on 2-d lattice. In the present paper, we apply a traffic model to this ecosystem. We deal with the population dynamics using cellular automata. Very recently, Sharma and Gupta investigated the impact of time delay on the dynamics of SEIR epidemic model using cellular automata [44]. They explored the effect of time delay on the epidemic dynamics. Here, we study the effect of migration on the population dynamics.

2. Model

The lattice Lotka–Volterra system (1) is combined with the traffic model for studying the migration effect. For simplicity, we consider one-dimensional lattice with two layers. Preys (predators) exist only on the first (second) layer. Fig. 1 shows the schematic illustration, where $x_i(t)$ and $y_i(t)$ mean the states of preys and predators at time t (at the position i) respectively.

$$x_i(t) = \begin{bmatrix} 1\,(X) \\ 0\,(O) \end{bmatrix}, \quad y_i(t) = \begin{bmatrix} 1\,(Y) \\ 0\,(O) \end{bmatrix}. \tag{2}$$

The predation (1a) is redefined in our traffic model. If both prey and predator occupy the same position, the predation occurs: the predator eats the prey. Then, the predation (1a) is defined by

$$X \to O \text{ (on 1st layer)}, \tag{3a}$$

$$Y + O \to 2Y \text{ (on 2nd layer)}. \tag{3b}$$

These reactions occur with the same rate r_Y (reproduction rate of Y). The reactions (1b) and (1c) can be represented by

$$X + O \to 2X \text{ (rate } r_X\text{) on 1st layer}, \tag{3c}$$

$$Y \to O \text{ (rate } m\text{) on 2nd layer}, \tag{3d}$$

where r_X and m are the reproduction rate of X and mortality rate of Y, respectively.

Simulations of CA model on one-dimensional lattice with two layers are carried out by local interaction. We explain the simulation procedure.

(1) Initially, preys (X) are distributed randomly on 1st layer lattice with probability x_0. A pair of Y is positioned at the center on 2nd layer. Other cells on 2nd layer are empty.
(2) All sites are updated by parallel processing.

Reaction processes are performed in the following steps:

(i) Reaction (3c). If a site is X on 1st layer, it reproduces offspring at the one of nearest-neighbor sites by rate r_X. If both neighboring sites are occupied by X, then we skip this reaction.