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Dynamics of Predators and Prey with Hunting and Escaping Activities in a Landscape with a Prey Refuge

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In this study, I constructed an agent-based model to simulate an integrative predator (wolf) - prey (rabbit) - plant (grass) relationship. When a wolf (rabbit) encountered a rabbit (grass), the wolf (rabbit) tended to move to the rabbit (grass) for hunting while the rabbit tended to escape from the wolf. These behaviors were characterized as the degrees of willingness for hunting (H_w for the wolf and H_r for the rabbit) and for escaping (E for the rabbit). I distributed prey refuges (with density N) in the grid space. To illustrate the effect of these variables, I plotted H_w-H_r grid maps containing information on the population density for each species. I examined how the densities of the three species varied with changes in these variables and analyzed the degree of influence of each variable on the density. Simulation results showed that E had the greatest influence on the ecosystem and that H_r had the next most important influence. H_w had the least influence. As N was increased, the effect of E was enhanced. The results mean that in an ecosystem consisting three hierarchical layers with a predation relationship, the species of the middle layer plays an important role in the ecosystem's stability. I briefly discussed how this proposed model can be applied to other ecosystems.

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I. INTRODUCTION

In the field of ecology and mathematical biology, population dynamics research is one of the topics that many researchers have been studying with great interest [1–3]. Understanding predator-prey dynamics is essential for comprehending the stability of ecosystems because an ecosystem consists of dynamically interacting subsystems that incorporate predator-prey relationships. For the understanding, Lotka and Volterra [4, 5] proposed a mathematical model (LV model) that described the dynamics of the fish population in the Adriatic. This model clarified the main features of species interactions and population cycles in predator-prey systems. However, the LV model is purely phenomenological. Even if one fits the model to a real dataset, the model does not provide information regarding what mechanism is driving the competitive interaction between species. To overcome this weakness, theoretical biologists and physicists modified the LV model to make more realistic models. The modified models incorporated non-linear relationships, called Holling type functions I, II, and III, to represent the interaction between the predator and the prey species [6,7]. The functions indicate the number of prey killed by one predator at various prey densities. Thanks to the functions, the modified models were successful in explaining what happened in various species in actual ecosystems [8,9].

However, even though these modified models include the concept of inter-specific interactions, some gaps still existed between the simulated and the actual phenomena. This is due to the limitations of the model, which were caused by the lack of consideration of the characterisics of individual behavior. In many cases, prey avoid being killed by predators either by defending themselves or by escaping, which determine the population behavior and are further connected to the ecosystem's stability [10]. In addition, the imitations also come from not including the prey-refuge concept. Many real ecosystems have prey refuges, which are a major contributor to the ecosystem's stability. A refuge is place where the predation risk is reduced or a habitat that is spatially separated [11–13], a phase of the prey's life history that is temporally separated. In recent years, researchers have been studied the influence of the prey-refuge concept in existing models and have presented some improved models [14,15]. In the improved models, two types of prey

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refuges exist: those that protected a constant fraction of prey and those that protected a constant number of prey. Refuges that protect a constant number of prey has been reported to lead to a stable equilibrium and to have a stronger stabilizing effect on population dynamics than refuges that protect a constant proportion of prey [16,17].

As mentioned above, the predator-prey model has increasingly been developed to include the key elements of ecosystems. Nevertheless, to my knowledge, there is still little model that involves individual behavior. This is because the individual behavior of a living creature is very complicated and depends on the conditions, which makes it difficult to handle mathematically. In this study, I proposed an agent-based model, thereby overcoming the two problems mentioned above. The model used in this study is a further extension of the model used by Cho and Lee [18] and by Lee *et al.* [19]. I also used the equation proposed by Kang and Lee [20] to implement the hunting and the escaping behaviors of an individual. Using the model, I explored how individual behaviors, such as hunting and escape, affect the ecological stability.

II. MODEL DESCRIPTION

My model used in this study was constructed in a space with $L \times L$ $(= 100)$ grids with periodic boundary conditions. In this model, for the purpose of contextual understanding in the simulation, I referred to the predator as a wolf, the prey as a rabbit, and the food of the rabbit as a grass. Two or more wolves (rabbits) cannot be together at a site.

In order to initially create and place wolves in the grid space, I generated a random number in each grid, and compared this number with a given variable W. A wolf was created in the corresponding grid site when the value of W was greater than the random number. The random number was generated by using the random function supported by MATLAB ver. 11.0 (Mathworks). The rabbits, the grasses, and the refuges were also positioned in the grid space by using the same method that was used to introduce wolves into the space. For rabbits, grass and refuge, the variables to be compared with the random number were given as R, G, and N. Thus, W, R, G, and N represent the initially given densities of wolves, rabbits, grass, and refuges, respectively. I assumed in this model that rabbits and grasses can be located in the same space as the refuge, but the wolf cannot enter the refuge. In the present study, the values of W, R, and G were fixed at 0.3. The refuge density, N, was simulated for 0.1, 0.2, and 0.3.

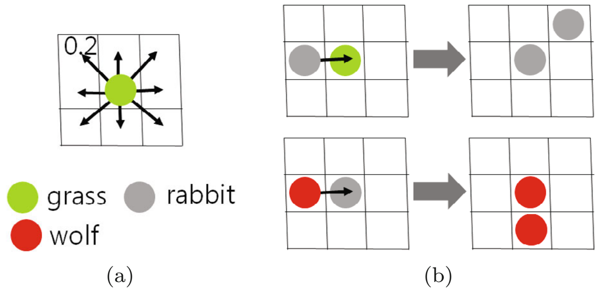

Fig. 1. (Color online) (a) Growth process of grass with a growth probability of 0.2. (b) Possible configurations encountered by a predator (wolf) and prey (rabbit) at a site. When the prey eats the grass (or the predator eats the prey), the prey (or predator) may give birth to a single offspring.

1. Species

In this model, wolves and rabbits were assumed to be constantly moving and not resting. Predation occurs when different species meet each other. Wolves and rabbits had a reserve of food, represented by a food-ration counter. The food reserve was interpreted as the health state of individuals. The counter increased after each meal (eating grass by rabbits and rabbits by wolves). The initially given value of the health state was 5. The following rules applied to predation and reproduction:

- The grass was allowed to spread towards the surrounding grid, and the diffusion probability was given as 0.2 (Fig. 1(a)). Through preliminary studies, I confirmed that the results of the present study do not change statistically, not even when the G values were varied between 0.1 and 0.4.
- When a wolf meets a rabbit, the wolf can eat the rabbit with a probability of 0.2. This relationship was similarly applied to the relationship between rabbits and grasses.
- When a wolf (or rabbit) was first introduced, or born, its health state was assigned an initial value of 5. Whenever a wolf (or rabbit) moved to a new site, its health state decreased by 1. The health state plays a role in limiting the life of the wolf individual from infinite persistence.
- When the wolf's (rabbit's) health state decreased below zero, the wolf (or rabbit) was removed from the system (individual death).
- If a wolf (or rabbit) consumed food (grass for a rabbit; rabbit for a wolf) at any time before death, its health state was restored to the original value of 5.
- When a wolf or a rabbit consumed food, it gave birth to a single offspring, according to a birth