



Effects of uniform rotational flow on predator–prey system

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ABSTRACT

Rotational flow is often observed in lotic ecosystems, such as streams and rivers. For example, when an obstacle interrupts water flowing in a stream, energy dissipation and momentum transfer can result in the formation of rotational flow, or a vortex. In this study, I examined how rotational flow affects a predator–prey system by constructing a spatially explicit lattice model consisting of predators, prey, and plants. A predation relationship existed between the species. The species densities in the model were given as S (for predator), P (for prey), and G (for plant). A predator (prey) had a probability of giving birth to an offspring when it ate prey (plant). When a predator or prey was first introduced, or born, its health state was assigned an initial value of 20 that subsequently decreased by one with every time step. The predator (prey) was removed from the system when the health state decreased to less than zero. The degree of flow rotation was characterized by the variable, R . A higher R indicates a higher tendency that predators and prey move along circular paths. Plants were not affected by the flow because they were assumed to be attached to the streambed. Results showed that R positively affected both predator and prey survival, while its effect on plants was negligible. Flow rotation facilitated disturbances in individuals' movements, which consequently strengthens the predator and prey relationship and prevents death from starvation. An increase in S accelerated the extinction of predators and prey.

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1. Introduction

A large number of organisms live in aquatic environments that are characterized by a predominantly running flow. Rivers and streams are particular examples of this type of environment. In lotic ecosystems, many organisms can be found occupying almost every available habitat, including the surfaces of stones, deep below the substratum, adrift in the current, and in the surface film. Insects have developed several strategies for living in the diverse flows of lotic systems. Some avoid high current areas, inhabiting the substratum or the sheltered side of rocks. In stronger current, species have developed weighted cases, attachments to anchored pads of silk, recurved clinging claws, suction cup-like appendages, and flattened, streamlined bodies [1,2]. Most organisms in lotic ecosystems rely heavily on the current to bring them food and oxygen [2]. As examples of positive and negative effects of flow on the predation, Trager et al. [3] showed that mean capture efficiency of *Artemia salina nauplii* by the barnacle, *Nobia grandis*, was maximized at the flow speed of 5 cm/s. On the other hand, Hansen et al. [4] reported that predation on black fly larvae by flatworms was shown to decrease with increasing flow as a result of reduced encounter rates (flatworms were less abundant in areas of high flow) and reduced probability of capture following encounters (flatworms are less efficient at capturing prey in higher flows). It has been known that in many cases, the water flow constitutes not only a foundation for the populations living therein, but also provides many ecological benefits to the populations [5,6].

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There are various interactions between biotic factors, such as animals, plants, and micro-organisms, and abiotic factors, such as temperature and water flow in lotic ecosystems. These interactions can be strengthened or weakened by flowing water, which directly affects the predation intensity. Variation in predation intensity has the potential to regulate species abundance in space and time in most systems [7–9]. The ability of predators to successfully detect and consume prey is a key factor in determining the potential regulating effect of predators on prey communities. Variation in many biotic and abiotic variables may affect a predator's ability to locate prey as well as escape or defense responses of prey to an approaching predator. For example, variations in water clarity [10], substrate type [11,12] and concentration of gases in aquatic systems [13,14] all have been shown to modify predator success.

Consequently, disruptions in the predation process can significantly affect the aquatic community [15,16]. The predation process is closely related to prey patch dynamics that can have significant consequences for the optimal foraging strategy of predators and the overall stability of predator–prey relationships [17–19].

In addition to lotic ecosystems, water flow also plays an important role in oceanic ecosystems. The impact of ocean hydrodynamic conditions on the biological activity of plankton species in predator–prey relationships has been a subject attracting the interest of researchers over the past several decades [20,21]. Two different processes, caused by flow, have been extensively studied. One process is vertical transport (e.g., advection, turbulent mixing) to bring nutrients to the upper layers of the ocean [22]. The other is horizontal (or lateral) transport mediated by mesoscale structures such as eddies, jets, and fronts [20,21,23–25]. These processes are the primary factors in the dynamics of plankton populations, providing the basic mechanism for patchiness in the plankton distribution and influencing key features, such as biological productivity.

As mentioned above, flow is one of the important keys to understand the aquatic ecosystems. However, to date, few simulation studies on the effects of the rotational flow on ecosystems have been performed because it is difficult not only to describe the interaction between organisms and flow mathematically, but also to quantify, by experimentally measuring, the changes in an organism's behavior caused by the flow characteristics [26]. Recently, along with the increase of the computer power, the method of computational fluid dynamics (CFD) has begun to attract considerable interest as a useful tool to theoretically understand an organism's behavior in fluid flow [27,28]. However, this approach still has limitations in terms of the short time dynamics. This method numerically solves the Navier–Stokes equation for fluid coupled with equations for the organism's behavior, which only focuses on the interaction between fluid and organism. The interaction occurs in a small area during a short time period, but not the stability of an aquatic ecosystem [29,30].

In the present study, to overcome the limitation, I constructed a simple lattice model consisting of three populations in a predator–prey system under uniform rotational flow. Using the model, I explored how the rotational flow affects the predator–prey system.

2. Model description

A simple ecosystem consisting of predator, prey, and plant was simulated on a 100×100 gridded space. A periodic boundary condition was used to minimize the boundary effect. Each lattice site was either occupied by predator, prey, or plant, or empty. Predators (and prey) could occupy the same site simultaneously. Double occupancy of plants at the same site was forbidden.

The initial distributions ($t = 0$) of the predator, prey, and plant were introduced into the lattice space by the distribution field for each species, $n_s(i, j)$, $n_p(i, j)$, and $n_g(i, j)$. The field denotes the number of individuals at lattice site (i, j) . I allowed at most one individual of each species to be present in any lattice site at $t = 0$. For $t > 0$, individuals can occupy the same lattice site while predator and prey move in the rotational flow effect.

The occupancy of the individual for each species in each lattice was given by thresholding based on the values S , P , and G , ranging from 0.0 to 1.0;

$$\begin{matrix} n_s(i, j), \\ n_p(i, j), \\ n_g(i, j) \end{matrix} = \begin{cases} 1, & \text{when } r(i, j) < S \text{ (for predator), } P \text{ (for prey), } G \text{ (for plant)} \\ 0, & \text{otherwise} \end{cases}$$

where $r(i, j)$ represents a randomly generated number at site (i, j) . Thus, the values of S , P , and G indirectly reflect the initially assigned species densities. In the simulation, the predator and prey initial density was $0.1 \leq S \leq 0.55$, $0.1 \leq P \leq 0.55$ with 0.05 increments, respectively. The value of G was set as 0.3. In the present study, each combination of S , P , and G was run for 10,000 iterations, and the simulation results were statistically averaged over 50 independent runs.

2.1. Homogeneous random space

In order to generate a lattice space in which individuals can randomly move, I assigned a random value, h , ranging from 0.0 to 1.0 to each lattice site. When a predator (or a prey) is surrounded by neighboring sites with h values, it is more likely to move into a site with a higher h value than a site with a lower h value (Fig. 1(a)). The probability for an individual to move to its neighbor sites is calculated as the ratio of the h value of a site to the summation of h values of the neighbor sites. For example, the probability for the individual to move in the top-right direction is calculated as $0.7/(0.7 + 0.1 + 0.5 + 0.2 + 0.1 + 0.3 + 0.4 + 0.3)$. The probability values for each direction were represented outside of the lattice box. In this figure, the predator has the highest probability to move into the top-right site.

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