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Analyzing Lamprey Population Growth and Sex Ratio Evolution Through Cellular Automata and Impact of Predation Efficiency and Sex Ratio on Lamprey Populations

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Abstract. Lamprey plays an important role in the ecosystem, and studying its population dynamics and the evolution of sex ratio is essential to maintaining the balance of the ecosystem. Faced with the challenges of complex environmental interactions and changes in population parameters, this study simulates the impact of gender ratio shifts on lamprey populations, revealing that imbalanced sex ratios can reduce growth and alter community dynamics. Adult mortality and recruitment rates significantly affect these dynamics. Maintaining balanced sex ratios is crucial for lamprey conservation and management. Changes in the sex ratio of lampreys can affect reproductive rates, reduce the stability of ecosystems, and lead to changes in resource allocation. The final result is that the change of the sex ratio of lamprey will reduce the stability of the ecosystem, other races and food chains will be affected, and the balance of the ecosystem will also be affected. Based on these two models, this experiment finally concluded that changes in the sex ratio of lampreys may affect the reproduction rate, reduce the stability of the ecosystem, affect other species in the food chain and species living in the same area, and ultimately affect the stability of the ecosystem.

Keywords: Lamprey, Cellular Automata, Lotka-Volterra, Food Web Complexity Assessment.

1. Introduction

The lamprey is a primitive jawless vertebrate that is widely distributed in both freshwater and marine environments. They play an important role in the ecosystem. Understanding the dynamics of lamprey populations and the evolution of sex ratios is important for maintaining the balance of ecosystems [1]. However, the study of lamprey populations faces many challenges, including complex environmental interactions and changes in population parameters [2][3].

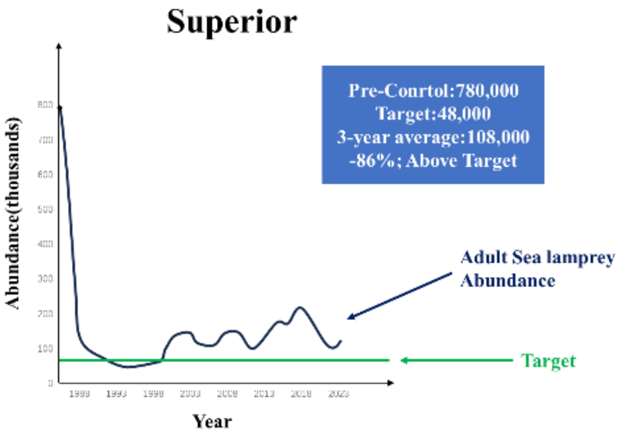
For this study, we developed the model for the impact of gender ratio changes in lampreys in a finite state, the aim was to investigate the impact on the larger ecosystem when lamprey populations can change their sex ratio [4][5]. Subsequently, the Lotka-Volterra Model of Differential Equations was developed, which simulates the effects of changes in the sex ratio of lampreys on prey populations by constructing differential equations with set parameters [6][7].

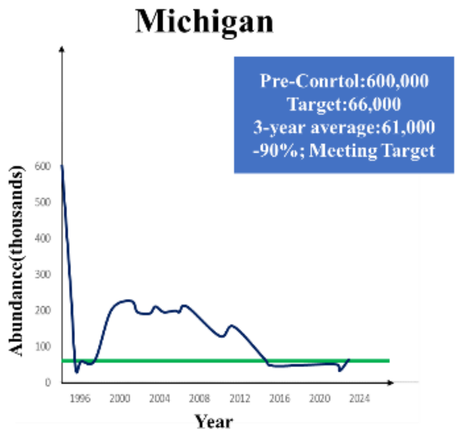
In this work, we simulated the changes in the sex ratio of lampreys and the changes in the population of lampreys under different resource conditions. The model for the impact of gender ratio changes in lampreys in a finite state perform environment parameter settings such as grid size, number of initial lampreys, amount of initial environment resources, and total number of time steps, initialize the number of resources and lampreys in the environment so that the resources are evenly distributed throughout the grid and the initial positions of the lampreys are randomized. The Lotka-Volterra Model of Differential Equations define the parameters. Initialize the initial conditions. These include, population size of male lampreys, population size of female lampreys and population size of prey. Define the time step and total simulation time and calculate the total number of steps. Initialize an array to store the number of lampreys and prey populations for each time step. Use a loop to traverse each time step and update the population size of lampreys and prey.

2. Simulating Lamprey Dynamics with Cellular Automata

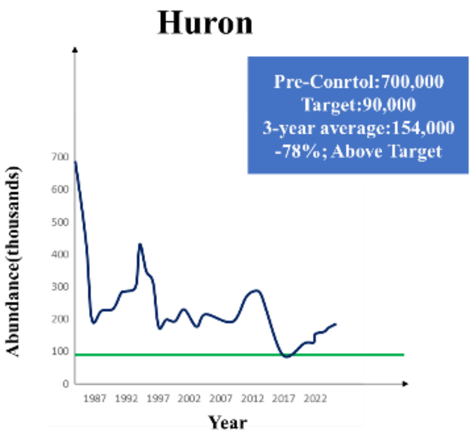
2.1. Lamprey Abundance by Lake

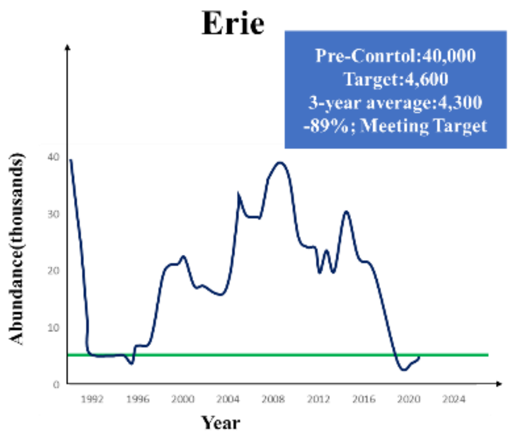
The data collected from http://www.glfc.org/status.php is displayed in Figure 1:



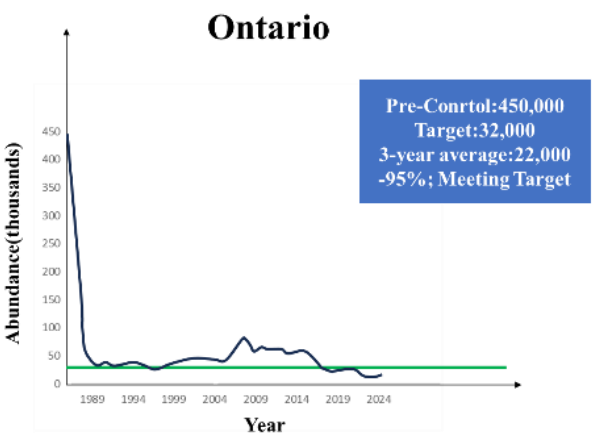


(a) (b)





(c) (d)



(e)

Figure 1. About lamprey abundance by lake

Table 1 summarizes the current status of each metric and a figure that highlights the whole-lake adult lamprey abundance estimates for each lake.

Table 1. Description of the current status of each indicator for each lake

Lake	Adult Lamprey Abundance Index	Lamprey Marking Rate on Lake Trout	Lake Trout Abundance
Superior	Above target, Flat	Above target, Flat	Flat
Michigan	Meeting target, Flat	Meeting target, Flat	Flat
Huron	Above target, Flat	Above target, Flat	Flat
Erie	Meeting target, Flat	Above target, Flat	Flat
Ontario	Meeting target, Flat	Meeting target, Flat	Flat

All in all, sea lampreys are resilient, and control must be ongoing, or sea lampreys will bounce back [8].

2.2. The Lampreys Sex Ratio

Mechanisms of sex determination in fishes can range from entirely genetic to entirely environmental, and their study provides opportunities for understanding how physiology and environment interact to determine sex. Fishes can also exhibit environmental sex reversal, where factors such as social structure and rearing temperature can override the primary genotypic sex, and result in a reversal of phenotypic sex that is then generally fixed for life. Environmentally triggered sex determination and reversals (herein termed sex determination) can lead to highly variable population sex ratios and are important when considering management tactics for valued, invasive, and hatchery-reared fishes.

Sex ratios of adult sea lamprey from the lentic, stream, and at-large populations differed substantially. Sex ratios of adult sea lamprey stocked as larvae in lentic and stream environments were biased towards males at a ratio of 3.8 males to one female in lentic areas and 2.3 males to one female in streams. The sex ratio of untagged adult sea lamprey captured from the same traps during the same years was 1.4 males to one female [9].

Additionally, Daily Mail mentions that researchers with the US Geological Survey (USGS) and Michigan State University found that slower sea lamprey growth rates during the larval phase of their development may increase the odds of sea lampreys becoming male. The study revealed that environments that lacked a plentiful supply of food for the sea lampreys had a male-skewed population - with 78 percent of sea lampreys becoming male after three years. By contrast, environments that were more conducive to growth produced only 56 percent of males [10].

2.3. The Establishment of the model for the impact of gender ratio changes in lampreys

Cellular automata are a cellular automata model that dynamically simulates the evolution of population growth, environmental resources, and sex ratio in lampreys. The main steps and analysis of the algorithm are described in Figure 2:

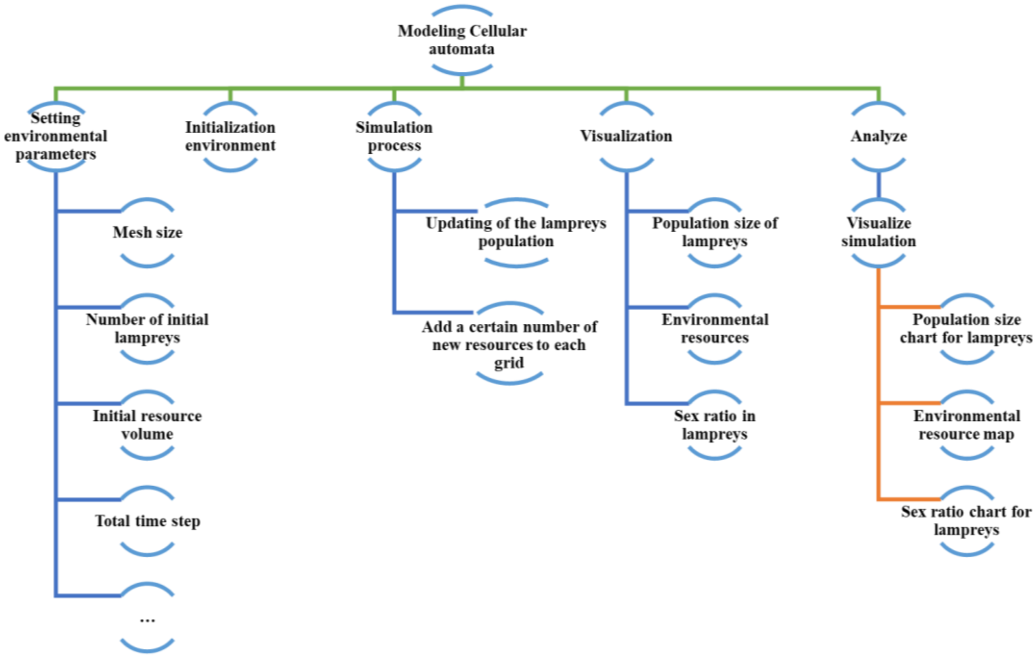


Figure 2. Flowchart for dynamic simulation of population growth, environmental resources, and sex ratio evolution in lampreys

2.4. The Solution of the Model for Simulating Lamprey Dynamics with Cellular Automata

Simulating Lamprey Dynamics with Cellular Automata [11] mainly uses some basic mathematical formulas and logical operations as follows:

a. Initialize resource distribution: generate a 50x50 matrix where each element is randomly generated and ranges between 0 and the initial number of resources.

b. Initialize the population of lampreys: generate a certain number of lampreys, distributed in different locations in the grid.

c. Adjusting the sex ratio calculates the ratio of the current resource amount to the total resource amount, and the algorithm adjusts the proportion of male lampreys according to this ratio.

d. Adding new resources: the algorithm is utilized to add a certain number of new resources at each time step.

e. Visualization: use the function to visualize the population, resources, and sex ratio of lampreys during the simulation, the result is visualized in the Figure 3:

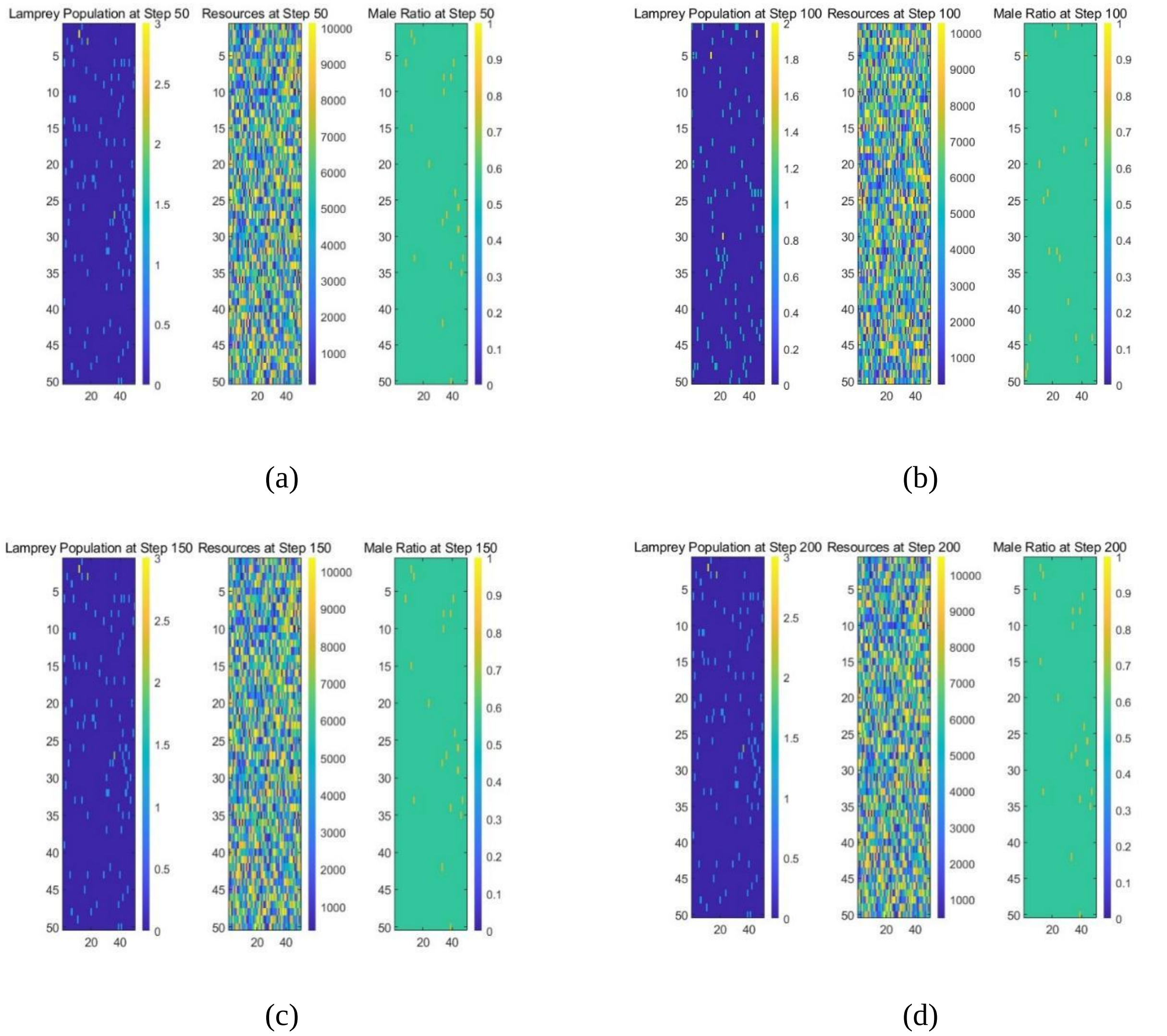


Figure 3. Visualization of populations, resources, and sex ratios of lampreys during simulation

The following conclusions can be drawn for the above four plots: the spatial distribution of populations of lampreys at a given time step, with color intensities indicating population densities at different locations in the grid; the spatial distribution of environmental resources in the environment at a given time step, with color intensities indicating resource abundance at different locations in the grid; and the spatial distribution of male lampreys at a given time step, with color intensities indicating the proportion of males at different locations in the grid. locations in the grid; and the proportion of male lampreys at different locations in the grid. By specifying the time step, it can be observed from the generative relationship map that the proportion of males may increase in environments with low resource abundance, while the proportion of males may decrease in environments with high resource abundance.

2.5. Results

The dynamic relationship between the number of lampreys and the sex ratio was reflected by modeling Cellular automata and adjusting the sex ratio.

During the simulation process, combined with the conclusions obtained from observing the images, changes in the sex ratio of lampreys may have the following effects on the ecosystem:

a. Impact on reproductive success: changes in sex ratio may affect the reproductive success of lampreys. In natural environments, changes in sex ratios may result in altered reproductive competition, which may affect population growth and distribution.

b. Reduced ecosystem stability: An increase in the proportion of males may also lead to

more intense competition and competition for resources. When the proportion of males increases, competition among lampreys may become more intense, especially when resources are limited, potentially leading to an ecosystem that is more susceptible to external pressures, reducing ecosystem stability.

c. Changes in resource distribution: Larger ecosystems may lead to changes in resource distribution. Changes in resource distribution may affect the distribution of ecological niches and populations of lampreys, which may further affect the sex ratio and ecological interactions of lampreys.

3. Model 2: Impact of Predation Efficiency and Sex Ratio on Lamprey Populations

3.1. The Establishment of Impact of Predation Efficiency and Sex Ratio on Lamprey Populations

The Lotka-Volterra [12] equation model is a simulation of lamprey population dynamics based on a numerical integration approach. In this simulation, the following parameters are defined:

- reproduction rate (r_M . r_F): the reproduction rate of male lampreys and female lampreys, respectively.
- natural mortality rate (d_M . d_F): the natural mortality rate of male lampreys and female lampreys, respectively.
- and predation efficiency (b_M . b_F): the predation efficiency of male lampreys and female lampreys, respectively.

In addition, there are the following variables:

- initial condition (M_0、F_0、P_0): represents the initial population size of male lampreys, female lampreys, and prey, respectively.
- time step (dt)and total simulation time (T): represents the time step and the total simulation time during the simulation process, respectively.
- initialization array (M、F、P): is used for storing the population sizes of the lampreys and prey at each time step.

The main logic of the algorithm is as Figure 4:

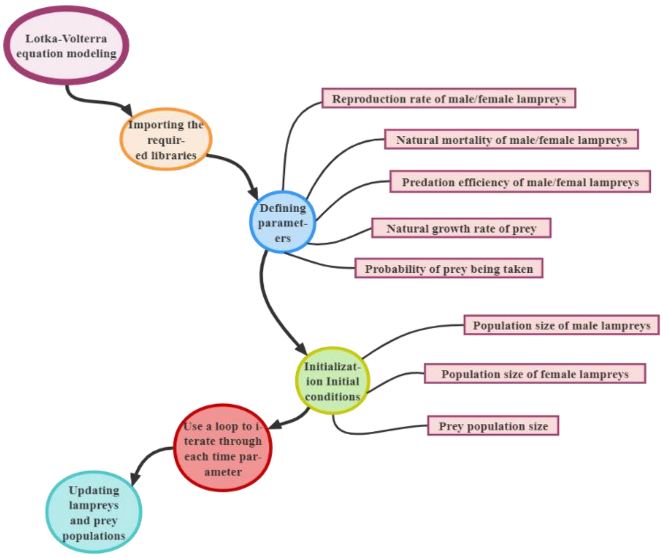


Figure 4. Flowchart for simulation of population dynamics in lampreys

3.2. The Solution of Model 2

The Lotka-Volterra equation model uses a simplified predator-prey model, also known as the Lotka-Volterra model. This model describes the interaction between two species, where one species is the predator (male and female lampreys) and the other species is the prey (prey). In this model, changes in the number of species are described by the following equation:

$$\frac{dM}{dt}=(r\_M*M-d\_M*M-b\_M*M*P)*dt \tag{1}$$

$$\frac{dF}{dt}=(r\_F*F-d\_F*F-b\_F*F*P)*dt \tag{2}$$

$$\frac{dP}{dt}=(r\_P*P-a*F*P)*dt \tag{3}$$

included among these:

$\frac{dM}{dt}$ denotes the rate of change in the population size of male lampreys over time.

$\frac{dF}{dt}$ denotes the rate of change in female lampreys' population size over time.

$\frac{dP}{dt}$ denotes the rate of change in prey population size over time.

r_M . r_F and r_P denotes the growth rate of male lampreys, female lampreys, and prey, respectively.

d_M and d_F denotes the natural mortality rate of male lampreys, and female lampreys, respectively.

b_M and b_F denotes the predation efficiency of male lampreys, female lampreys, respectively.

a denotes the probability that the prey is preyed upon.

These equations describe the changes in species populations over time, where parameters such as growth rate, natural mortality rate, and predation efficiency influence the trends in species populations. Through numerical integration methods, the changes in species numbers over time can be simulated and the simulation results can be visualized by plotting graphs, as shown in the Figure 5:

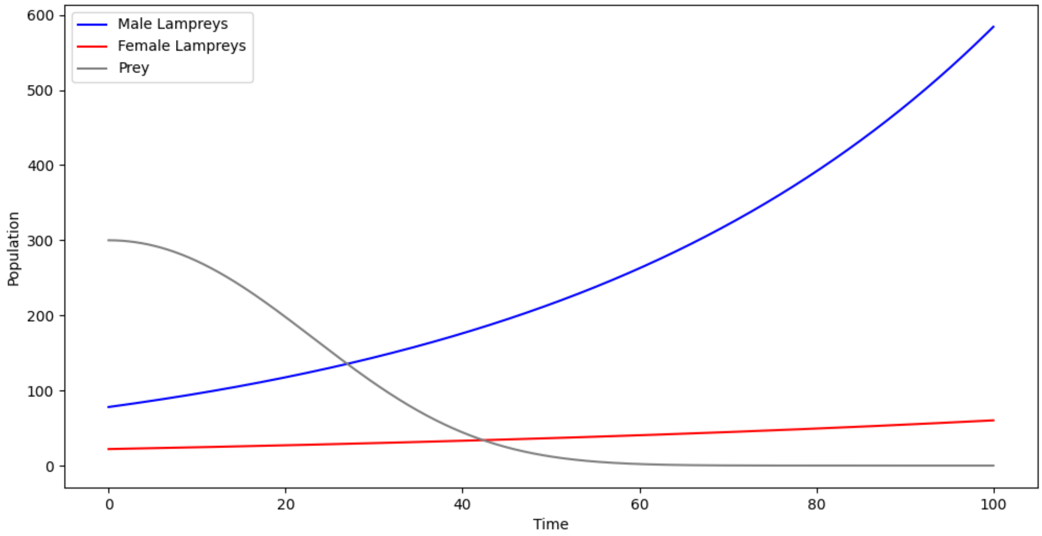


Figure 5. Structured population model simulation

The following summaries can be drawn from the images and reasonable extrapolations:

a. As the number of lampreys increases, the number of preys continues to decrease, and male lampreys increase much faster than female lampreys.

b. The effect of decreasing prey on male lampreys is small, and male lampreys still show an exponential increase when the number of preys tends to 0.

c. It can be reasonably extrapolated that male lampreys can live parasitically, while female lampreys are weak in parasitism.

3.3. Results

During the simulation of the model, combined with the conclusions obtained by observing the images, the change in the sex ratio of lampreys may have the following effects on the ecosystem:

a. Decreased stability of the ecosystem: an increase in the proportion of males in lampreys

will lead to a decrease in the abundance of environmental resources and a decrease in the stability of the ecosystem. the number of competitor populations of lampreys may follow the trend of the number of food items, the number of organisms parasitized by lampreys, and the number of predators of lampreys follows the trend of the number of lampreys. Although changes in population size vary among populations, a large reduction in organisms at the bottom of the food chain can also reduce ecosystem stability.

b. Affecting the food chain: lampreys are a source of food in some ecosystems, and changes in their sex ratio may affect the predators that feed on them. If the proportion of male and female lampreys in a predator's diet changes, this may lead to adjustments in predator abundance and behavior.

c. Impact on other species: lampreys inhabit habitats such as lakes or oceans, and changes in their sex ratios may lead to changes in their utilization patterns in different habitats, affecting other species inhabiting the same area.

d. Impact on ecosystem balance: As an important ecosystem member, changes in the sex ratio of lampreys may lead to changes in the abundance and distribution of other groups of organisms. This may have a knock-on effect on the balance of the entire ecosystem.

4. Conclusions

In this paper, we modeled the effects of different sex ratios of lamprey's populations on the population itself, other species, and the environment from the perspective of ecological niches, and then generalized to larger ecosystems based on this.

This paper first developed the Simulating Lamprey Dynamics with Cellular Automata, which is intended to simulate the effects of changes in the sex ratio of lampreys on population size and the environment. Subsequently, the Impact of Predation Efficiency and Sex Ratio on Lamprey Populations was developed, which simulates the effects of changes in the sex ratio of lampreys on prey populations by constructing differential equations with set parameters. Based on these two models, the following conclusions were finally obtained: changes in the sex ratio of lampreys may affect their reproductive success (decrease/increase), changes in the distribution of resources, other species in the food chain, and species inhabiting the same area, etc., which ultimately affects the stability of the ecosystem. Then a Population Dynamics Model of Lampreys was developed in this paper. The model simulated the integrated metrics of lamprey's populations based on changes in sex ratio and assessed the performance of the populations in controlling parasites, food chain roles, ecosystem service provisioning, and environmental adaptations by assigning weights to these metrics. Finally, based on this model, it was concluded that lampreys have strong environmental adaptability, and it plays a positive role in maintaining the stability of the ecosystem.

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