

Study on Sex Ratio of Lampreys Based on Simulated Ecosystem-Food Web Model

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How to cite this paper: Zhao, Z.Y., Hao, X.Q. and Xia, J.Y. (2024) Study on Sex Ratio of Lampreys Based on Simulated Ecosystem-Food Web Model. *Journal of Applied Mathematics and Physics*, 12, 2959-2989.

<https://doi.org/10.4236/jamp.2024.128177>

Received: July 18, 2024

Accepted: August 24, 2024

Published: August 27, 2024

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Abstract

Lampreys, as an important participant in the ecosystem, play an irreplaceable role in the stability of nature. A variety of models were used to simulate ecosystems and food webs, and the dynamic evolution of multiple populations was solved. The temporal changes of the biomass and the health of the ecosystem affected by the population of Lampreys in other ecological niches were solved. For problem 1, Firstly, a simple natural ecosystem is simulated based on the threshold model and BP neural network model. The dynamic change of the sex ratio of lampreys population and the fluctuation of ecosystem health value were found to generate time series maps. Lampreys overprey on low-niche animals, which damages the overall stability of the ecosystem. For problem 2, We used the Lotka-Volterra model to construct ecological competition between lampreys and primary consumers and predators. Then, the Lotka-Volterra equations were solved, and a control group without gender shift function was set up, which reflected the advantages and disadvantages of the sex-regulated characteristics of lampreys in the natural environment. For problem 3, The ecosystem model established in question 1 was further deepened, and the food web was simulated by the Beverton-Holt model and the Logistic time-dependent differential equations model. The parameters of the food web model were input into the neurons of the ecosystem model, and the two models were integrated to form an overall biosphere model. The output layer of the ecosystem neural network was input into the food web Beverton-Holt and Logistic differential equations, and finally, the three-dimensional analytical solution was obtained by numerical simulation. Then Euler method is used to obtain the exact value of the solution surface. The Random forest model was used to predict the future development of lampreys and other ecological niches. For problem 4, By investigating relevant literature, we normalized the populations of lampreys and a variety of fish as well as other ecological niche animals, plants and microorganisms in the same water area, set different impact weights of lampreys, constructed weight evaluation matrix, and obtained

positive and negative ideal solution vectors and negative correlation proximity by using TOPSIS comprehensive evaluation method. It is concluded that many kinds of fish are greatly affected by the sex regulation of lampreys.

Keywords

BP Neural Network Model, Lamprey, Beverton-Holt and Logistic Differential Equations Systems, TOPSIS Comprehensive Evaluation Method

1. Introduction

1.1. Problem Background

Lampreys (**Figure 1**), also known as lampreys, are cartilaginous gnathless parasites biologically belonging to the order Lampreys, the Class Agathylostoma. Lampreys are similar in appearance to snakes and eels, and their bodies are slender and eel-shaped. [1] Lampreys have a funnel-shaped mouth with a circle of teeth, which are round suckers that can be attached to other fish. A single lampreys can kill about 40 pounds of fish, and the survival rate of fish attacked by lampreys is only 1 in 7. In about 15 months of parasitism, sea lampreys can gain up to 100 times their weight. Once they reach sexual maturity, they move to a river or stream for 4 - 8 weeks to lay eggs, after which they die. [2] Some animals do not have only two fixed options for sex selection, that is, there are only two sexes, female and male. Although most species naturally exhibit a 1:1 sex ratio at birth, various factors can also cause the sex ratio to switch later in life. This is called adaptive sex ratio change. Lampreys play different roles in different ecosystems and have different impacts. It lives in lake or Marine habitats and migrates upstream to spawn. This mathematical modeling aims to solve the relationship between the sex ratio of lampreys and environmental resources. The rate of development in the larval stage of lampreys is determined by the ratio of male to female, and the rate of growth is determined by the influence of environmental food supply. Food is scarce, and males can make up 78% of the population. When the food is plentiful, the male share of the population drops to 56%.



(a) Cyclostoma lampreys [3]

(b) Japanese lampreys [3]

Figure 1. Lamprey.

1.2. Restatement of the Problem

Considering the background information and restricted conditions identified in the problem statement, we need to solve the following problems:

- Problem 1: When lampreys change the sex ratio in order to adapt to changes in the resource environment, what effect does it have on the larger ecological environment?
- Problem 2: What are the advantages and disadvantages of the ability of lampreys to change the sex ratio according to resource and environmental conditions?
- Problem 3: Is the stability of the ecological environment affected by the change in the sex ratio of lampreys?
- Problem 4: Does an eel population with a shifting sex ratio have a positive impact on other players in the ecosystem?

1.3. Our Work (Figure 2)

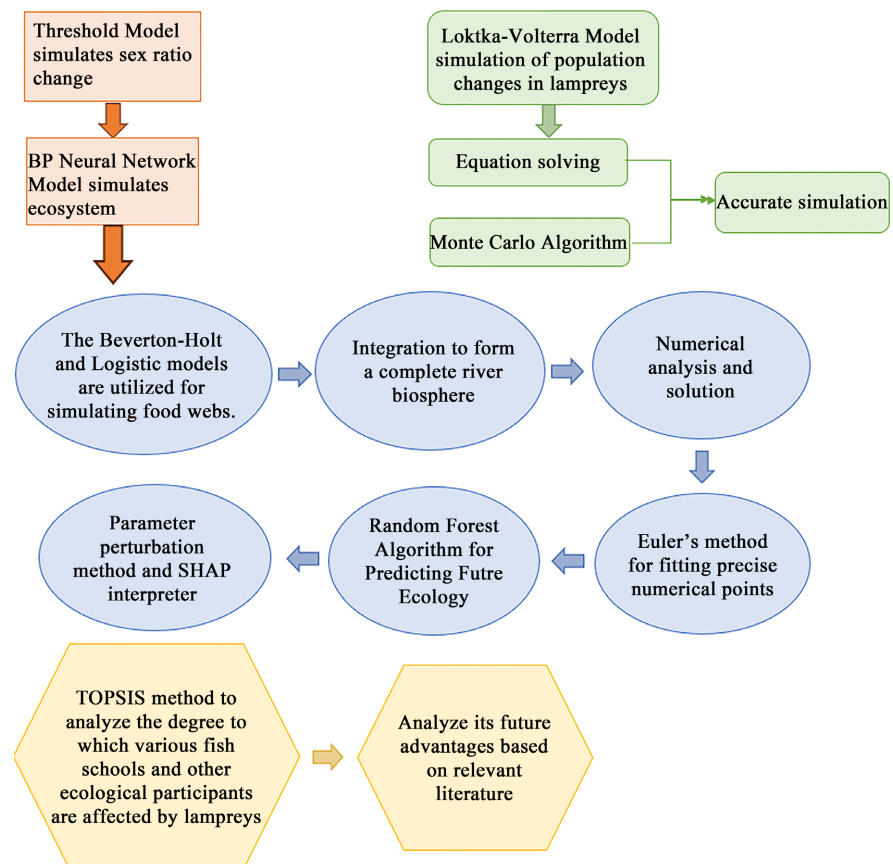


Figure 2. Overview of work.

2. Assumptions and Justifications

The following basic assumptions are made to simplify problems.

Assumption: The proportion of male and female in the initial lampreys community was uniform.

Justification: At the beginning of the experiment, lampreys, as the species initially entering the basin, should maintain an even sex ratio.

Assumption: Food is plentiful in the initial state.

Justification: In addition, this environment should have the characteristics of sufficient food at the initial stage, so as to further reflect the ecological characteristics of the natural watershed and make the observation of the role of lampreys on the ecology clearer.

Assumption: No man-made fishing or interference or extreme natural disasters.

Justification: Because the experimental background here is a natural river far away from human activity.

Assumption: The reproductive system is normal in the entire lamprey community.

Justification: Lampreys have a strong survival ability, and the proportion of genetic defects and lesions is very small.

3. Notations (Table 1)

Table 1. Notations.

Symbol	Description
e	error
o	exportation
r	The natural growth rate of each group
a	Predation rate
b	Food use efficiency
F	Food supply
G	Growth rate
K	Environmental capacity of each population
Gr	Sex ratio
Pr	Predator growth rate
Rf	Randomness factor
Grp	Growth rate parameter
$\varepsilon randn()$	Random climatic factors in the environment

*Other notation instructions will be given in the text.

4. Model I: BP Neural Network Model

4.1. Sex Ratio Change

Because the sex ratio of lampreys fluctuates with the difference of food supply in the environment, we first analyzed the sex ratio fluctuation and built a simple ecological model based on the threshold model (Figure 3) to simulate the sex ratio and growth rate changes of lampreys population.

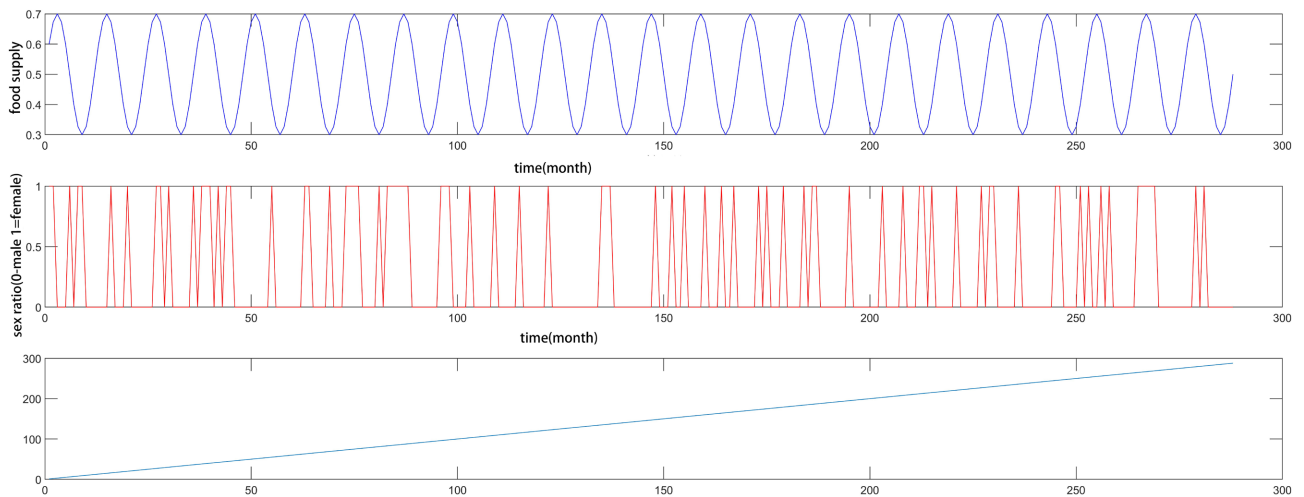


Figure 3. Time series of changes in food supply and sex ratio of lampreys.

The model is represented as a sex ratio simulation model based on food availability and growth rates. The sex ratio of lampreys population was simulated by calculating the growth rate and introducing randomness factor in the model. The sex is determined by the threshold value, and the randomness factor is introduced to increase the randomness of the model, so that the simulation effect is more in line with the variability of the natural ecosystem.

The proportion of sex is affected by food, this process has a certain randomness, and the random probability function of its sex is determined:

$$Pa \sim (0,1)$$

$$GR = F \times GRP \times (1 + RF \times randn()) \quad (1)$$

The dynamic sex ratio of lampreys simulated by the above model is used as the initial value of the sex ratio change of lampreys in the ecosystem.

4.2. Simulated Ecosystem

Since the ecosystem of the whole river has various influencing factors on the population of lampreys, lampreys play an important role in the survival and reproduction process of the ecosystem. The system has the characteristics of diversity, transitivity and reflexivity. The dynamic process of the ecosystem under the action of lampreys was preliminarily simulated through multiple groups of neurons in the BP neural network model (Table 2).

The following factors exist in the model of natural ecosystems:

- Food availability: Food availability affects the growth rate and sex ratio of lampreys.
- Lampreys sex: Male and female lampreys differ in predatory ability, reproductive ability, and mortality.
- Predators: Predators prey on lampreys, both eggs and adults.
- Seasonality: Seasonality affects food availability and the number of predators.

Therefore, the following neurons are set in the neural network to simulate the

dynamic process of the interaction of lampreys in the whole ecosystem of the population.

- Food supply neuron: This neuron represents the level of food supply in the environment and is controlled by parameters.
- Growth rate neuron: This neuron represents the growth rate of individuals in a lamprey community, influenced by food availability and growth rate parameters.
- Sex neuron: This neuron represents the sex of an individual and is determined by randomness and a threshold of growth rate.
- Spawning neuron: Indicates the laying of eggs by a female individual.
- Hatching neurons: represent the hatching of eggs, *i.e.* the generation of a new generation.
- Growth neuron: Represents the growth of a newborn individual.
- Predation neurons: The effect of predation on the community is controlled by predation rate.
- Ecosystem health Neuron: This neuron indicates the health of the entire ecosystem, taking into account the food supply and the number of larvae and adults.

Food supply, lampreys sex ratio, total lampreys, total males, total females, and ecosystem biological richness were taken as feature variables and target variables, and corresponding weight estimates were added to each neuron to achieve random authenticity of the model.

Table 2. Model parameters and weights.

Food supply	Radius	Change rule	Lampreys sex	Determining factor
Initial value: 0.5	0 - 1	Sinusoidal curve, simulating seasonal changes	Initial ratio: 1:1	Growth rate and threshold
Growth rate	Threshold value	Natural enemy	prey	seasonality
Food supply * Growth rate parameter	0.5	Predation rate: 0.1	Eggs and adult lampreys	Change in material supply: 0.2

The initial value of the sex ratio calculated by the above threshold model is brought into the BP neural network model, and the operation principle is as follows.

Calculation from input layer to hidden layer:

$$z_1 = \omega_{11} \cdot F + \omega_{21} \cdot G + \omega_{31} \cdot Pr + b_1$$

$$a_1 = \sigma(z_1) \tag{2}$$

$$z_2 = \omega_{12} \cdot F + \omega_{22} \cdot G + \omega_{32} \cdot Pr + b_2$$

$$a_2 = \sigma(z_2) \tag{3}$$

Calculation from hidden layer to output layer:

$$z_{output} = \omega_1 \cdot a_1 + \omega_2 \cdot a_2 + b_{output}$$

$$a_{output} = \sigma(z_{output}) \tag{4}$$

Calculation error:

$$e = \frac{1}{2} \cdot (Gr - a_{output})^2 \quad (5)$$

Backpropagation: Updating weights and bias by gradient descent, using the chain rule to calculate the gradient.

$$\frac{\partial e}{\partial \omega_i} = -(Gr - a_{output}) \cdot a_{output} \cdot (1 - a_{output}) \cdot \omega_i \quad (6)$$

$$\frac{\partial e}{\partial b_{output}} = -(Gr - a_{output}) \cdot a_{output} \cdot (1 - a_{output}) \quad (7)$$

$$\frac{\partial e}{\partial a_i} = -(Gr - a_{output}) \cdot a_{output} \cdot (1 - a_{output}) \cdot \omega_i \quad (8)$$

$$\frac{\partial e}{\partial z_{output}} = \frac{\partial e}{\partial a_{output}} \cdot \frac{\partial a_{output}}{\partial z_{output}} \quad (9)$$

A complete operation of the model is equivalent to a natural evolution of the ecosystem. The above model is repeated five times, and the five times' data are generated to train the neural network. The time of each ecological cycle is set at 24 months, which is roughly in line with the adaptability and evolution state of the river ecosystem in the face of foreign organisms. After Matlab calculation, it is shown that the accuracy of the training model of this neural network is 95%, indicating that the output data of this neural network has a high statistical confidence.

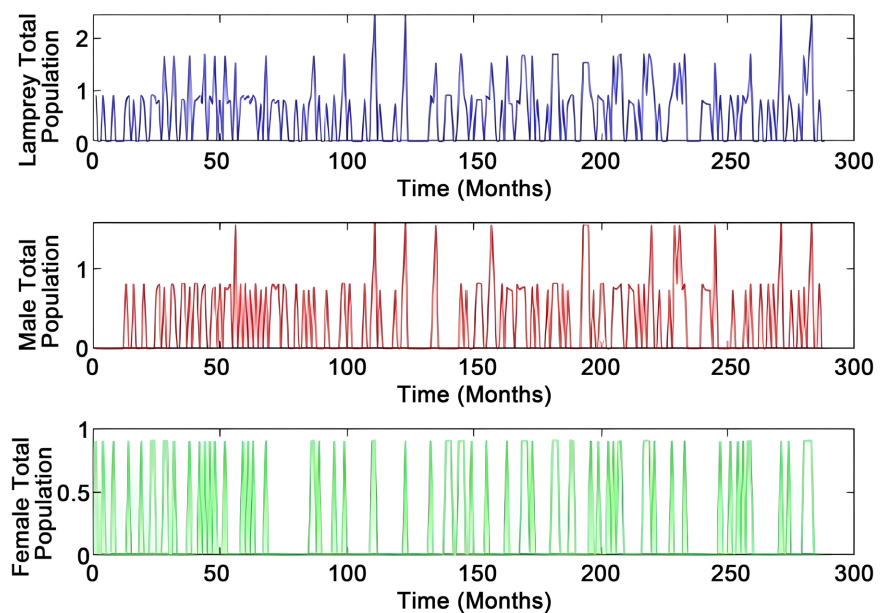


Figure 4. Time series of changes in the population and sex ratio of lampreys.

In order to more accurately predict the impact of lampreys on the entire ecosystem, after the training of the neural network, the trained model was used to predict the changes in lampreys community and ecosystem in the next 24

months, and the results were shown in the time series diagram of the total amount of lampreys (**Figure 4**), the total amount of males, the total amount of females, and the biological richness of the ecosystem (**Figure 5**).

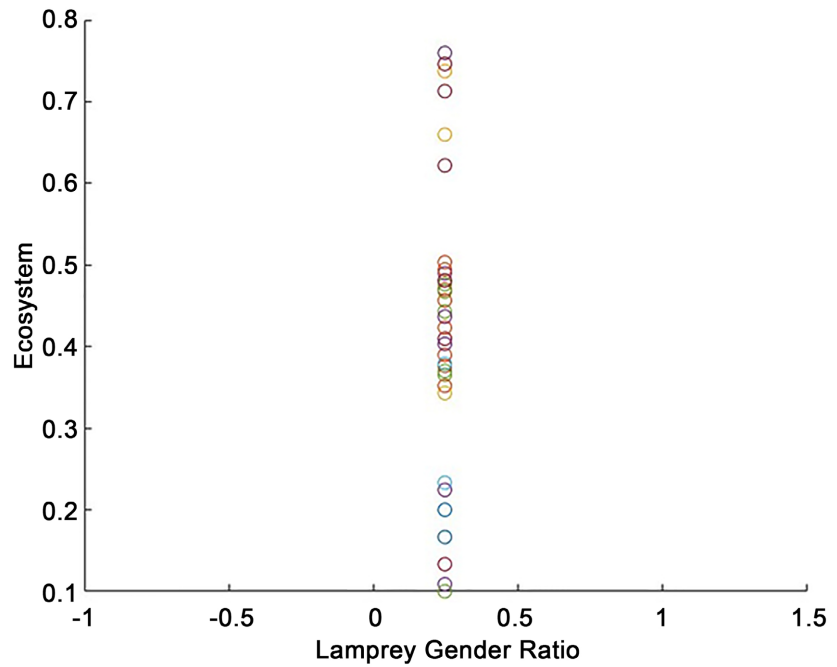


Figure 5. Scatter plot of lamprey sex ratio over time.

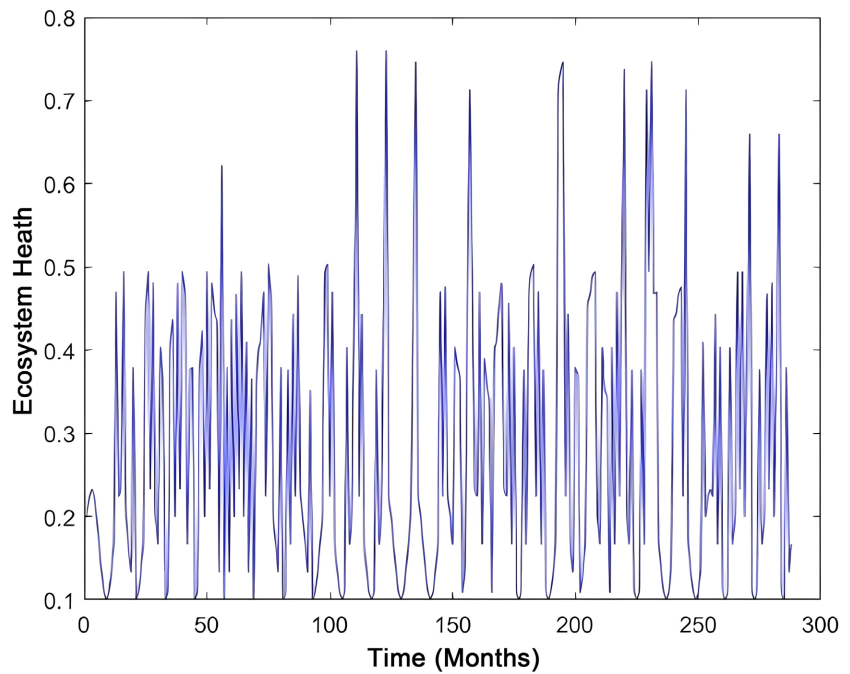


Figure 6. Time series in ecosystem health values.

4.3. Result

There is a strong positive correlation between ecosystem biological richness and

total male population. Due to food competition and lampreys sex reversal, the peak value of total male population generally avoids the peak value of total female population, and the number of lampreys strongly affects the ecosystem biological richness. The growth rate of lampreys showed a regular temporal fluctuation. Ecosystem health value also has a strong positive correlation with the total male population (Figure 6). When food is scarce, the total male population peaks and lampreys have sufficient food, indicating that lampreys will overprey on their lower trophic level at this moment, which will destroy the original ecological cycle and cause great damage to the health state of the ecosystem. In summary, Lampreys population tends to cause the number of species lower than their own food chain to decrease too rapidly (Figure 7), causing food chain disruption, disrupting the normal ecological homeostasis of low and high nutrient levels, and generally damaging the stability of the ecosystem. [4]

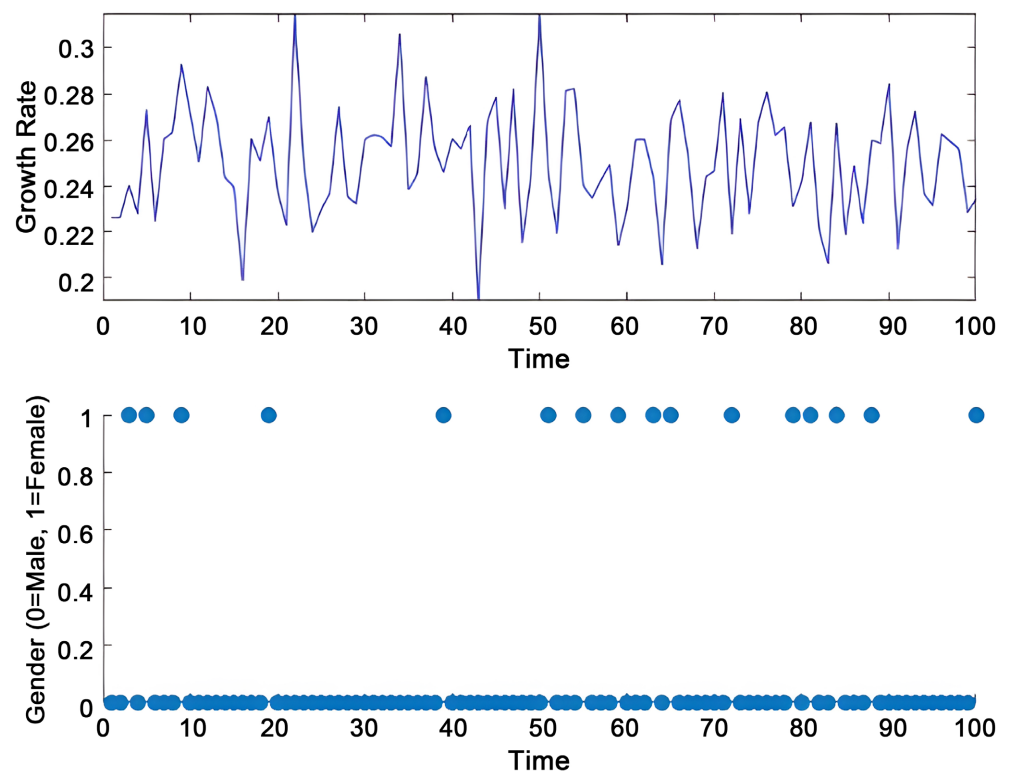


Figure 7. Time series of sex ratio and growth rate.

5. Model II: Lotka-Volterra and Monte Carlo Simulation Models

5.1. Lotka-Volterra Model

Based on the analysis of the survival advantages and disadvantages of the lampreys population, the Lotka-Volterra model based on the interspecific competition relationship can be constructed to analyze the evaluation of the population with controllable sex ratio based on the predator-prey interaction between the independent lampreys population and the entire ecosystem. Starting with the

basic relationship between predator and prey, the variables of the Lotka-Volterra equation are preliminarily as follows:

Female lampreys (prey) population equation:

$$\frac{dX}{dt} = \Upsilon_X X \left(1 - \frac{X}{K_X} \right) - g(F) a_{XF} XF - a_{XZ} XZ + \varepsilon_X \text{randn}(t) \quad (10)$$

Male lampreys (prey) population equation:

$$\frac{dY}{dt} = \Upsilon_Y Y \left(1 - \frac{Y}{K_Y} \right) - g(F) a_{YF} YF - a_{YZ} YZ + \varepsilon_Y \text{randn}(t) \quad (11)$$

Food (primary consumer) population equation:

$$\frac{dF}{dt} = \Upsilon_F F \left(1 - \frac{F}{K_F} \right) - b_{XF} XF - b_{YF} YF \quad (12)$$

Higher predator (Z) population equation:

$$\frac{dZ}{dt} = \Upsilon_Z Z \left(1 - \frac{Z}{K_Z} \right) - b_{XZ} XZ - b_{YZ} YZ \quad (13)$$

Female Lampreys fertility rate (RX) equation:

$$R_X = \Upsilon_{\text{birth},X} \cdot g(F) + \varepsilon_X \text{randn}(t) \quad (14)$$

Female Lampreys fertility (RY) equation:

$$R_Y = \Upsilon_{\text{birth},Y} \cdot (1 - g(F)) + \varepsilon_Y \text{randn}(t) \quad (15)$$

X is the population of female lampreys; Y is the population size of male lampreys; F is the population size of food (primary consumer); Z is the population of higher predators; When food is plentiful, the sex ratio is even; When food is scarce, there are more males. To reflect this characteristic, a function $g(F)$ of food quantity is constructed to describe the degree of gender bias.

This is a sigmoid function for the amount of food in the range (0, 1), which maps a real number to the interval (0, 1) for binary classification. When the food quantity is low, the gender deviation is large, and when the food quantity is high, the gender deviation is small. The specific function expression is as follows:

$$g(F) = \frac{1}{1 + e^{-k(F-F_0)}} \quad (16)$$

where k controls the steepness of the sigmoid function and F_0 is the central point of the sigmoid function, the function of the minus sign in front of this function is to adjust the female fertility to reflect the relatively few females when the food level is low. In this case, the minus sign in front of the male and the minus sign in front of the female are to achieve the regulatory effect of food level on the sex ratio.

Specifically, the effect of these two minus signs is to introduce a regulatory mechanism in the model that causes female fertility to decrease when food levels are low, thereby reducing the relative number of females. This is to better reflect the relative ease with which males gain the advantage of survival and reproduc-

tion in resource-poor environments, thereby affecting the dynamics of the sex ratio.

The sex regulation of lampreys as a population characteristic, in order to more clearly analyze the unique survival advantages and disadvantages of lampreys, the lampreys population was used as an experimental group, and an unregulated control group was set up for experimental comparison, because the competition between female and male lampreys and the interaction between food and higher predators were considered when the food supply was sufficient. In this way, the fertility of both females and males is affected by food, which affects the sex ratio of the population.

The gender shift function $g(F)$ was deleted from the Lotka-Volterra equations in the control model, which reflected the uniform sex ratio caused by the irreversible reversal.

In order to restore the uncertainty of natural environmental factors in the real ecosystem and the possible individual death phenomenon in the population, random disturbance terms are introduced behind the equation of Lampreys population as an independent variable in the Lotka-Volterra equations. In ecology, these disturbance terms can represent the unpredictable factors in the ecosystem, which are interpreted as environmental variability in this model

The perturbation term can model uncertainties caused by variability in environmental factors (such as climate, water quality, etc.) that may have a random effect on the number of females and males.

In the whole Lotka-Volterra model system, this interference term belongs to Gaussian white noise and follows the normal distribution of random process. Indicates an incomplete understanding of the behavior of the system and the complex influence of the system on external and internal factors. Because randomness and uncertainty are prevalent in real ecosystems,

introducing these disturbance terms in modeling helps to more accurately capture the dynamic behavior of the system.

The mathematical representation of Gaussian white noise is usually described using normally distributed random variables. The perturbation term in the differential equation for the number of females can be expressed as:

$$\varepsilon_X \times randn() _ \varepsilon_X \times randn()$$

Among $randn()randn()$ Generates a standard normally distributed random number with a mean of 0 and a variance of 1. Multiply by $\varepsilon_X _ \varepsilon_X$ to scale it to the appropriate disturbance coefficient, Scale it to the appropriate disturbance coefficient.

Similarly, for the perturbation term in the differential equation for the number of males, the expression is:

$$Y \times randn() _ Y \times randn()$$

The characteristics of the random normal distribution (**Figure 8**) are demonstrated by using Matlab.

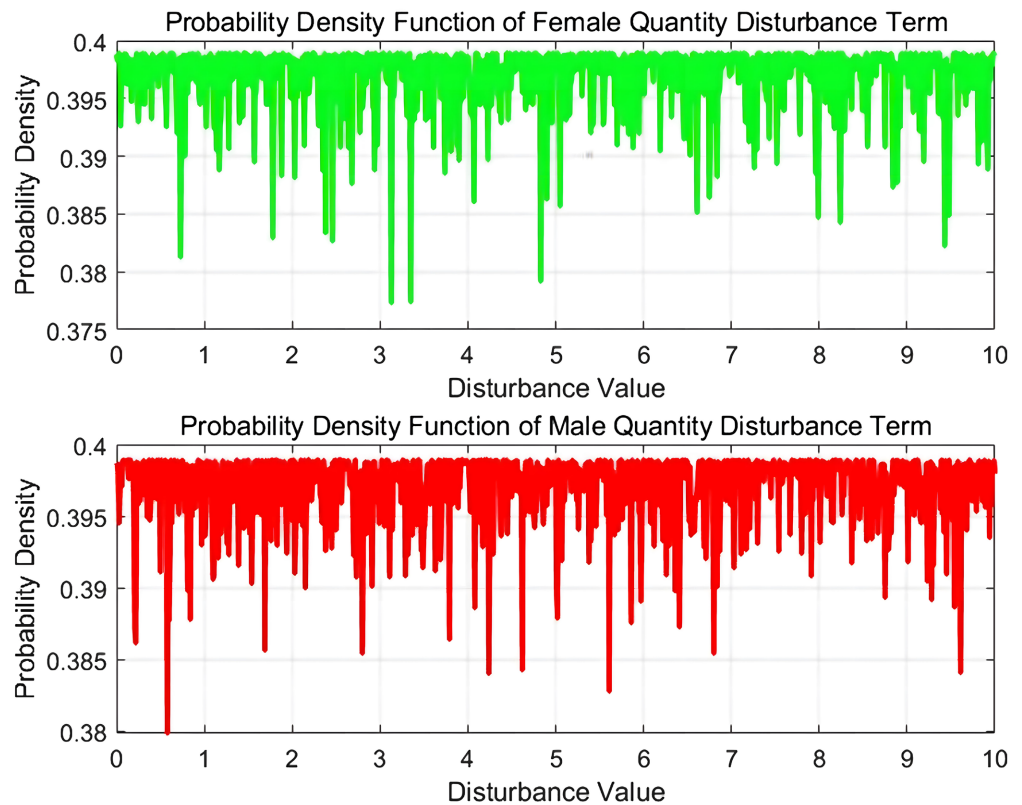


Figure 8. Statistical distribution of Gaussian white noise.

These two perturbation terms introduce randomness at each time node, reflecting fluctuations in the ecosystem due to environmental uncertainty or other factors. These random terms can lead to small fluctuations in population numbers throughout the simulation, giving a more realistic representation of the complexity of the ecosystem.

Matlab was used to solve the Lotka-Volterra ordinary differential equations of the experimental group and the control group respectively, and the corresponding solving algorithm constructed the corresponding time-varying solution space for the analytic solution (Figure 9) of the differential equations and expressed it in the form of graphs.

In the analytic solution space, it can be seen initially that the number of female lampreys in the experimental group was significantly higher than that of males in the early stage, but with the passage of time, the number of females decreased rapidly and the number of males increased rapidly, which may be attributed to the large difference between food supply and population consumption. However, the overall population showed a large upward trend, while the gender growth in the control group was just the opposite. It increased rapidly, with more males in the early stage, showing a significant downward trend, and still showing an overall upward trend. It can be speculated that male fish may encounter more battles and dangerous situations in the river system, so the mortality rate is higher.

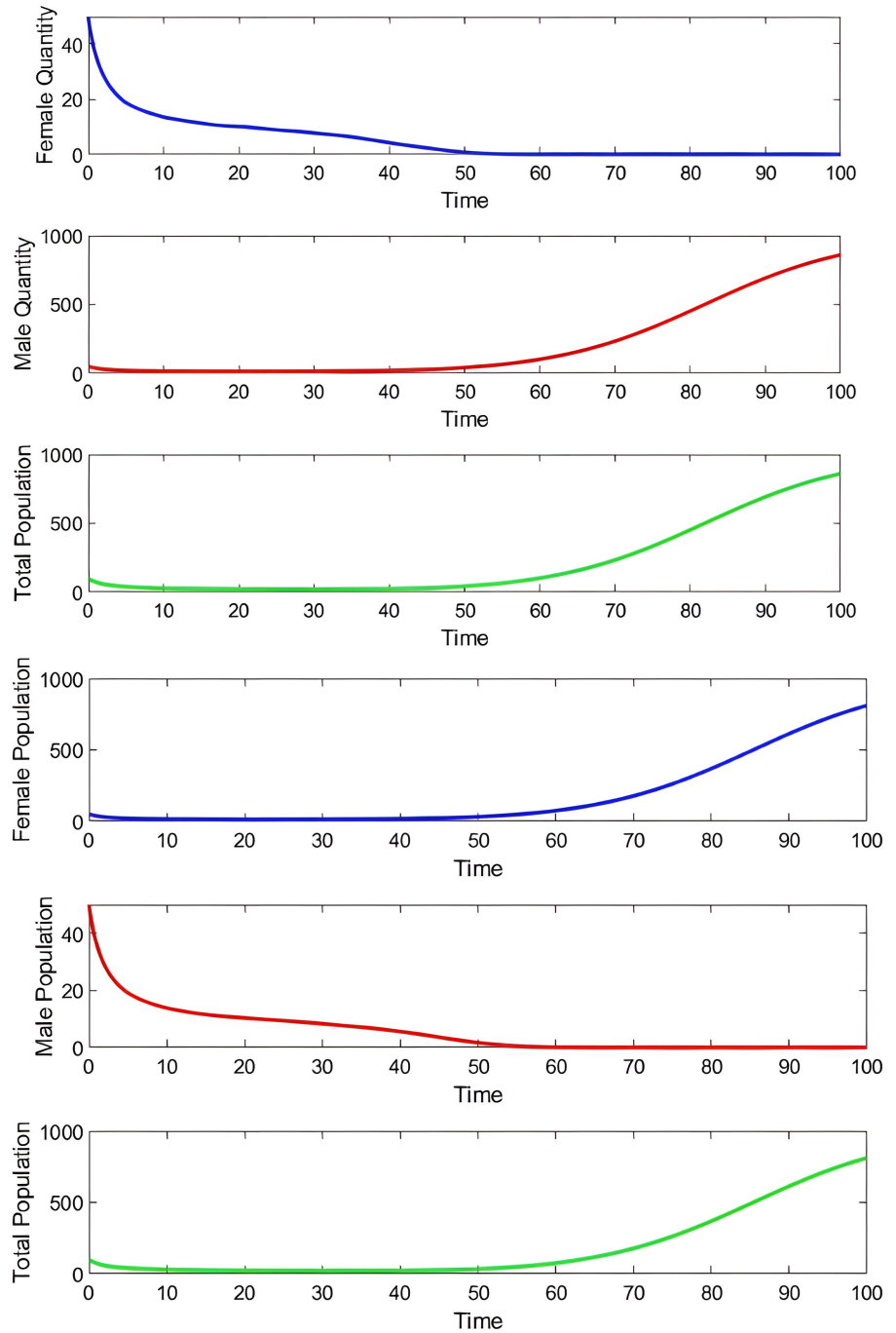


Figure 9. Analytic solution space of Lotka-Volterra equations.

5.2. Monte Carlo Simulation

The above Lotka-Volterra model initially constructed a dynamic system based on river ecology with differential equations. However, in natural river ecology, the situation is often complex and changeable and difficult to accurately predict, so the analytical solution of the model inevitably has many systematic errors with the real situation. In order to improve accuracy and better evaluate the advantages and disadvantages of lampreys population, The simulated ecosystem

constructed by the threshold model and BP neural network in problem 1 was used to generate a large number of bounded data of the survival of random lamprey populations and non-sex inversion populations by using the random matrix method. As a training cluster, the simulation experiment with randomness was carried out under the Lotka-Volterra model by using the Monte Carlo simulation method and inputting the training set data.

In ecology, Monte Carlo simulation is often used to simulate the dynamic process of an ecosystem with large randomness, taking into account the influence of uncertain factors on population changes. In this experiment, the dynamics of the ecosystem were simulated by randomly selecting white noise term, initial conditions such as population number and slight sex ratio in the ecosystem, natural growth rate of each population, predation rate and other parameters. Based on the differential equations of the Lotka-Volterra model, multiple training sets are input into the dynamic processes of the ecosystem. The Gaussian white noise term still introduces randomness through $\varepsilon_x randn()$ and $\varepsilon_y randn()$ to simulate the effect of uncertainty on the system.

5.3. Result

Four images, from top to bottom, depict changes over time in the total community size between lampreys and normal bisexual vertebrates. According to the time analysis, the number of males in the early lampreys group is much higher than that of females, and most of the individuals in the community are composed of males, that is, males are more adaptable to the changeable environment and lack of food in the early stage of population development, while in the early stage of normal bisexual vertebrates, there are more females, that is, they cannot control the gender adaptation environment and maintain the balance of individual gender numbers. In the middle period, the number of males and females in Lampreys is reversed, the environment is suitable, and the food is more abundant, resulting in more females than males, and the population is ready to expand. However, the number of females is still higher than that of males in normal bisexual vertebrates, and the number of females is higher. [5]

The variation of the quantity over time was similar to that of the total community quantity. In the later two communities, the number of females was much higher than that of males. The error caused by the analytical solution of Lotka-Volterra equations was corrected here, and the population intended to reproduce on a large scale and broaden the living environment. The Fourier analysis method was used to analyze the fluctuation of lampreys population (**Figure 10**).

Spectrum resolution: The spectrum shows a significant amplitude at a particular frequency, which means that the community growth has a clear periodicity at that frequency. This may be explained by some inherent ecological process or interaction in the ecosystem that causes oscillations in community numbers.

Spectrum amplitude: Frequencies with larger amplitudes in the spectrum in-

dicating that these frequency components have a larger impact on community growth. The amplitudes were large at multiple frequencies, suggesting that community growth was influenced by multiple ecological processes or interactions that could lead to instability.

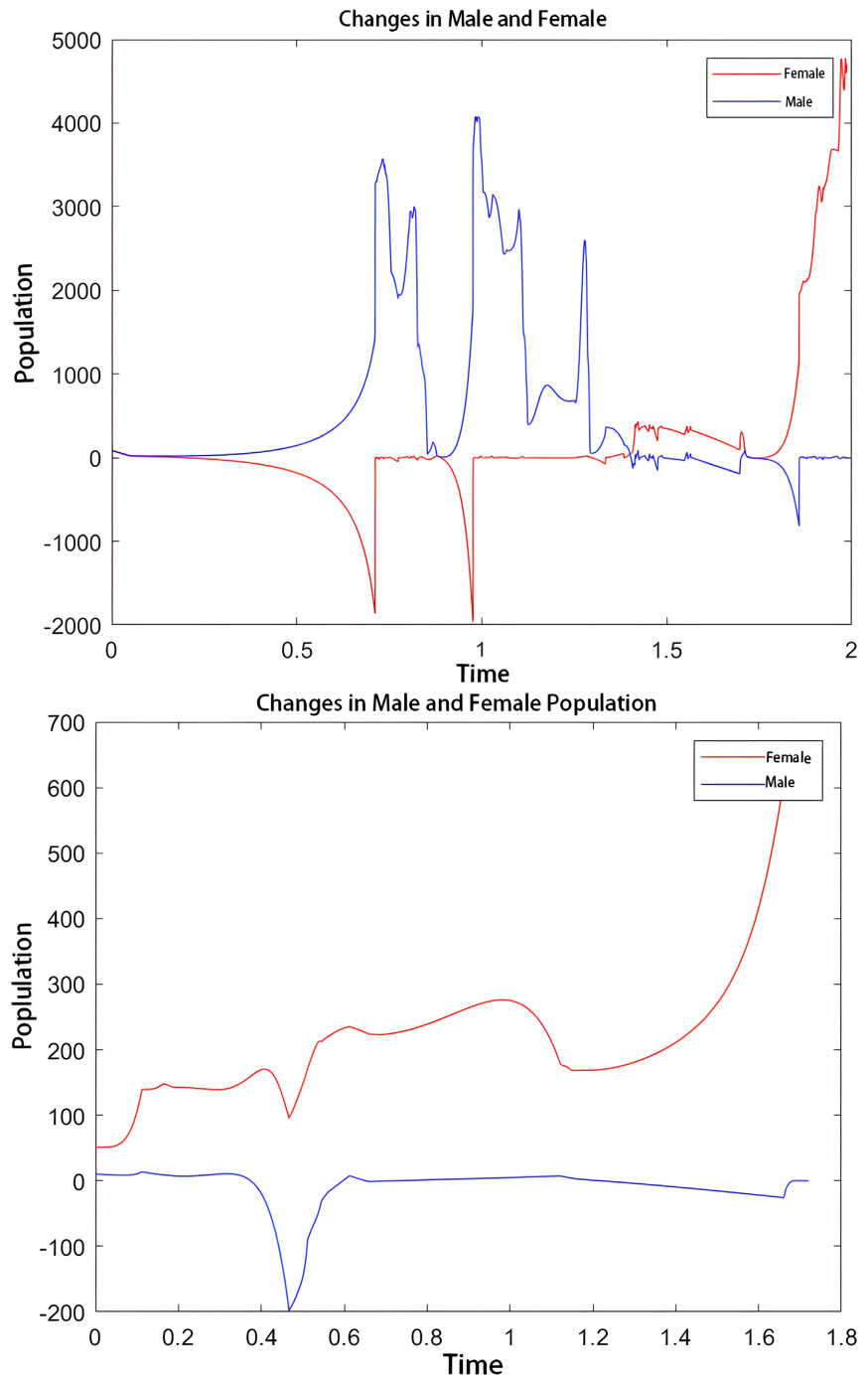


Figure 10. Changes in male and female population.

Therefore, on the whole (**Figure 11**), the advantage of lampreys population is that the population number and gender number difference show a sudden jump

at a specific time, and the remaining stages are almost flat, with few small fluctuations. The sex ratio imbalance caused by sexual reversal can prevent the population from explosive growth leading to complete depletion of food and population extinction, and the population will die out under too rapid and intense external disturbance.

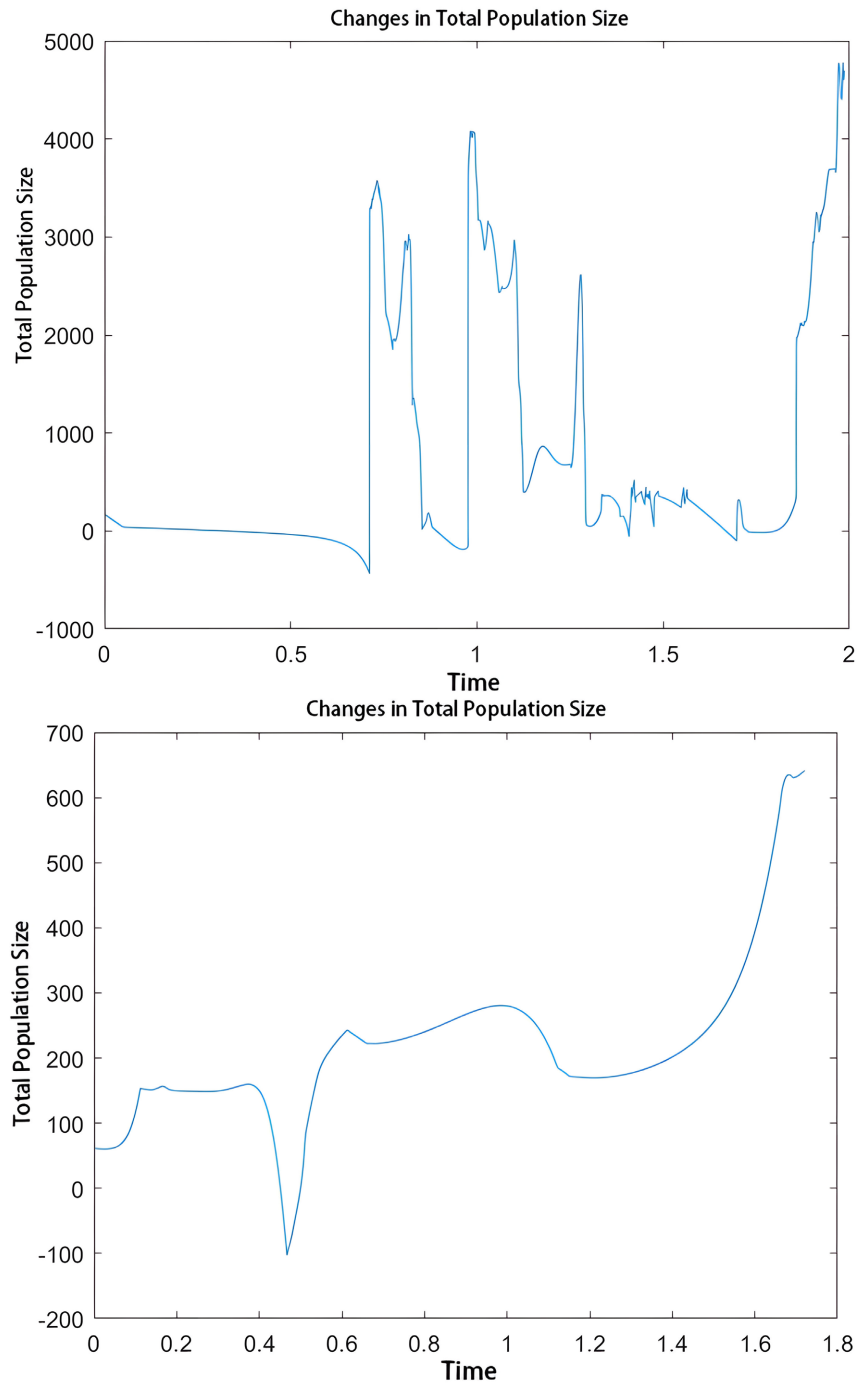


Figure 11. Changes in total population size.

Therefore, on the whole, the advantage of lampreys population is that the

population number and gender number difference show a sudden jump at a specific time, and the remaining stages are almost flat, with few small fluctuations. The sex ratio imbalance caused by sexual reversal can prevent the population from explosive growth leading to complete depletion of food and population extinction, and the population will die out under too rapid and intense external disturbance.

The disadvantage of the population is that the overall fluctuation is relatively large, and the growth rate of the fluctuation is very high, because the internal population system is relatively unstable. If the external interference with severe time and great intensity is encountered when the number of a single-sex presents a step form, it will easily lead to the disappearance of a certain sex and lead to the extinction of the population in the ecosystem here, especially in the upstream spawning position. Populations are more vulnerable.

6. Model III: Deepen the Ecosystem and Food Web Integration Model

6.1. Deepen the Ecosystem Model (Figure 12)

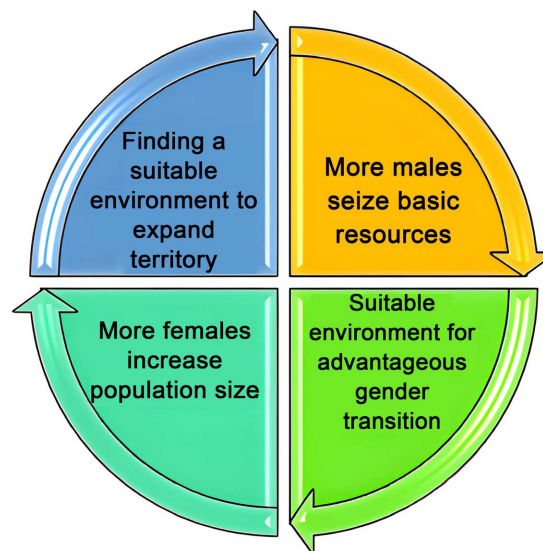


Figure 12. Characteristic map of lampreys ecosystem.

In order to further analyze the impact of the dynamic process of lampreys' sex ratio on various aspects of ecosystem stability, we further improved the simulated ecosystem built based on BP neural network to be closer to the real river ecosystem. This river ecosystem model reflects different conditions in the upstream and downstream. The upstream lampreys die after spawning and predators decrease. However, the overall biological richness is high, and the downstream is vice versa. Moreover, the influence factor of temperature, seasonal temperature change, is added. At the same time, the habitat will also be weakly affected by natural disasters, so the habitat change is also regarded as a random noise with weak interference.

The above variables were added to the original BP neural network model to build an ecosystem model closer to the natural river, and the sequential evolution of the number of lampreys of different genders and the total biomass of the ecosystem was obtained by Matlab calculation.

The following are distribution calculations and predictions for two genders and the overall population by Matlab. (Figures 13-17)

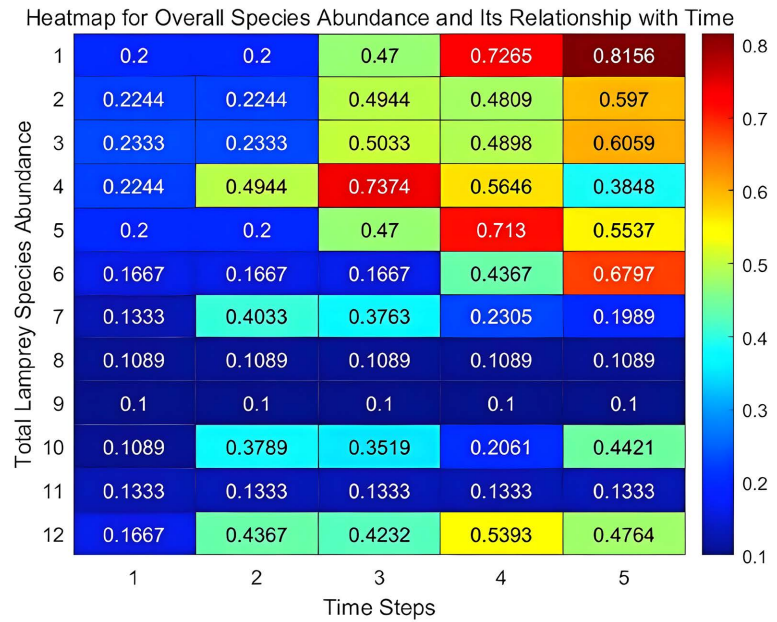


Figure 13. Heatmap for overall species abundance and its relationship whit time.

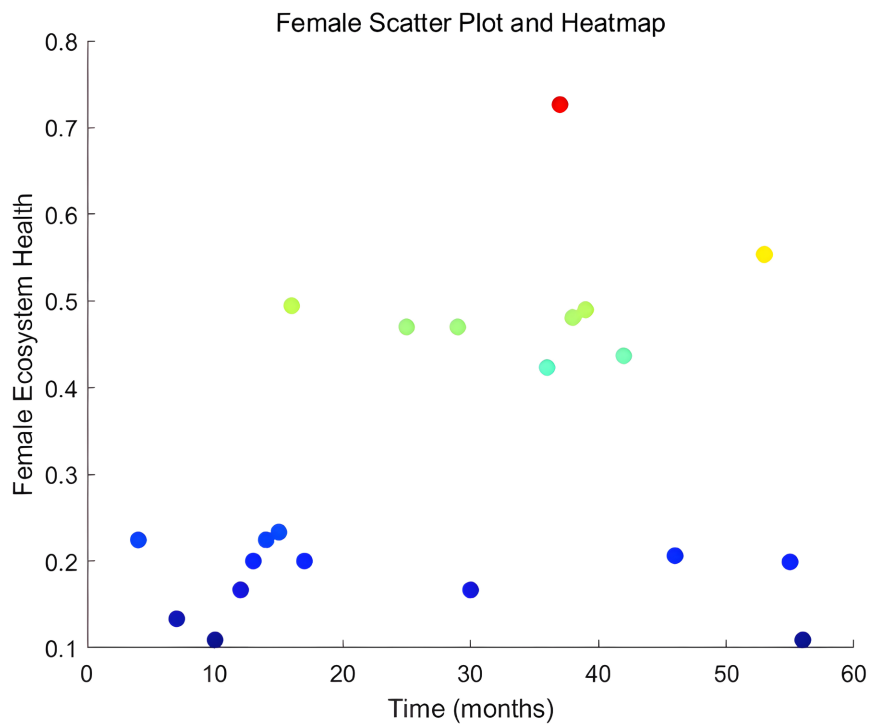


Figure 14. Female scatter plot and heatmap.

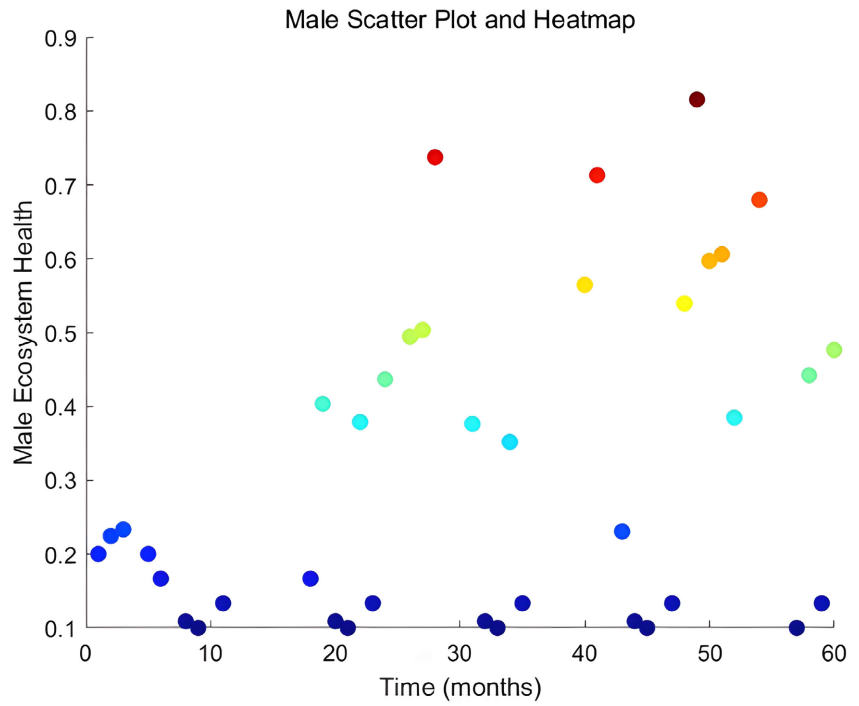


Figure 15. Male scatter plot and heatmap.

In order to better express the dynamic system of the whole small biosphere, a separate analysis of the food web relationship composed of only biological populations can better reflect the results of the interaction between various biological populations.

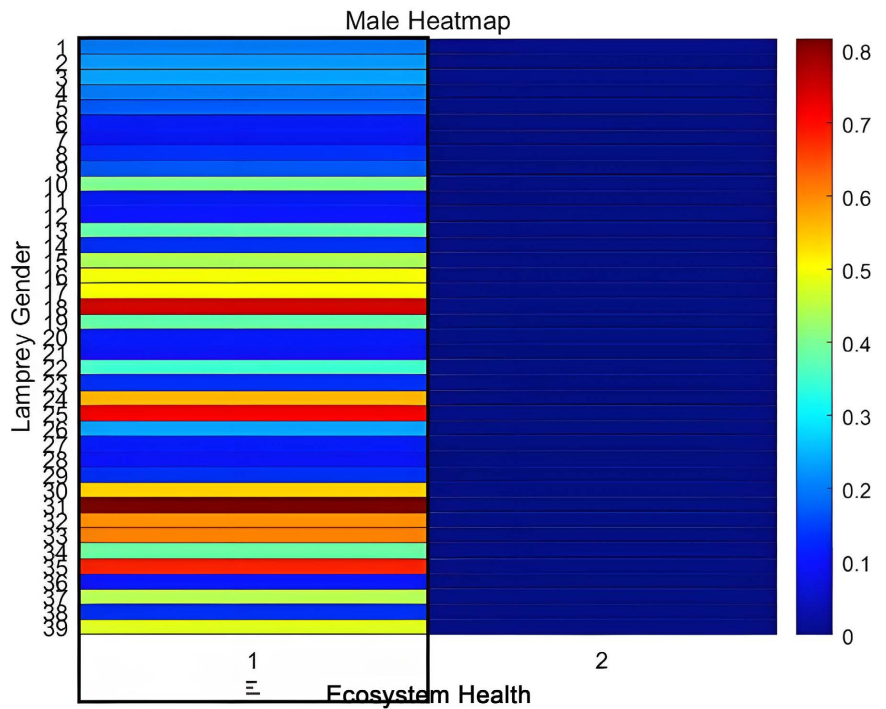


Figure 16. Spatial distribution of males.

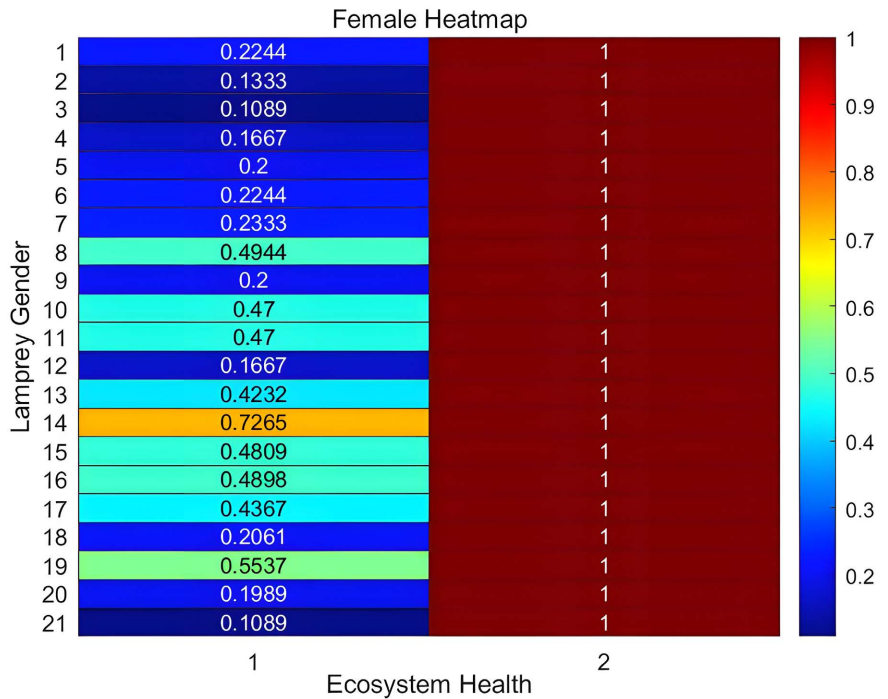


Figure 17. Spatial distribution of females.

6.2. Beverton-Holt and Logistic Models Simulate Food Webs

Beverton-Holt model was selected to assume that there were producers, primary consumers (food), lampreys (secondary consumers) and tertiary consumers (predators) in the food web, and the dynamic changes of the three were determined by a series of relevant parameters such as food quantity and predation relationship from different trophic levels. Some noise terms were also set as the intensity of random disturbance. Based on the above relationship, the time-dependent Beverton-Holt differential equations for the survival of each member of the food web are presented:

$$\frac{dP}{dt} = \alpha P - \beta P \cdot H + \epsilon \cdot randn() \tag{17}$$

$$\frac{dH}{dt} = \gamma H \cdot P - \delta H \cdot L + \epsilon \cdot randn() \tag{18}$$

$$\frac{dL}{dt} = \epsilon L \cdot H - \zeta L \cdot Pr \cdot H + \epsilon \cdot randn() \tag{19}$$

$$\frac{dPr}{dt} = \eta Pr \cdot L - \theta Pr + \epsilon \cdot randn() \tag{20}$$

P is the number of producers, H is the number of herbivores, L is the number of lampreys, is the model parameter, and is the intensity of the control random disturbance.

Since the above Beverton-Holt model has a relatively simple dynamic change mode among species, which is quite different from the real food web, in order to reflect the dynamic effect of populations at different levels, a logistic model was added to the Beverton-Holt model, which included the initial population quan-

tity, the inherent growth rate of the population r , and the

following factors: Each logistic is a partial differential equation of population number and time t , and the population function is a function of double independent variables, namely, environmental tolerance K and time t . Since population number is also limited by environmental tolerance, Logistic is a system of partial differential equations, and the increase of equations adds boundary conditions to the analytical solution of the model of population dynamic change. Make the solution more precise.

Logistic equations:

$$\frac{\partial P}{\partial t} = \alpha P - \left(1 - \frac{P}{K}\right) + \epsilon \cdot \text{randn}(\cdot) \quad (21)$$

$$\frac{\partial H}{\partial t} = \gamma H - \left(1 - \frac{H}{K}\right) + \epsilon \cdot \text{randn}(\cdot) \quad (22)$$

$$\frac{\partial L}{\partial t} = \epsilon L - \left(1 - \frac{L}{K}\right) + \epsilon \cdot \text{randn}(\cdot) \quad (23)$$

$$\frac{\partial Pr}{\partial t} = \eta Pr - \left(1 - \frac{Pr}{K}\right) + \epsilon \cdot \text{randn}(\cdot) \quad (24)$$

Firstly, the analytical solutions of the Beverton-Holt ordinary differential equations were solved in order, and the characteristics of their solutions were taken as the boundary conditions of the logistic partial differential equations. Then, the three-dimensional analytical solution space of the whole food web model composed of Beverton-Holt and logistic was obtained through the Matlab operation program. The population evolution of producers, primary consumers, lampreys and predators over time under the constraint of K is reflected respectively.

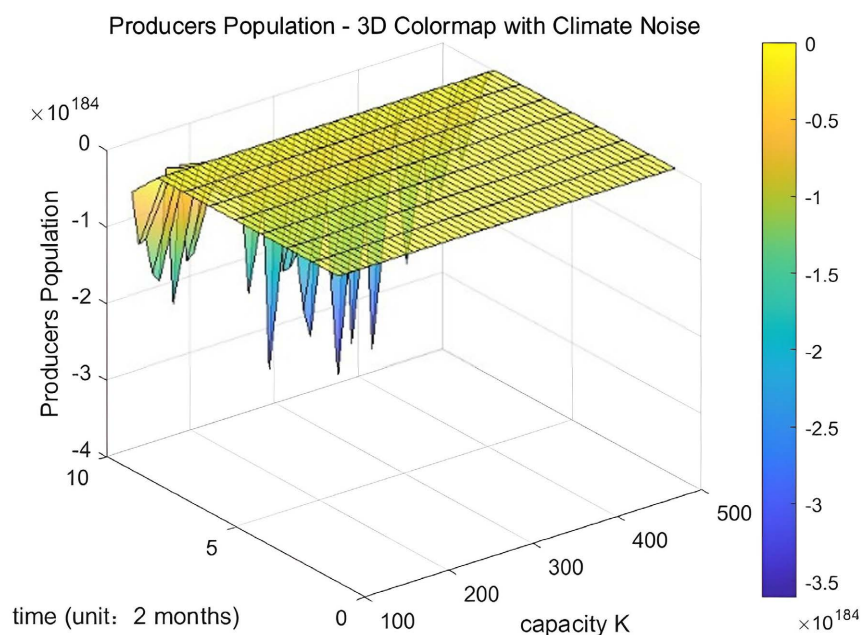


Figure 18. Producers' population-3D colormap with climate noise.

It can be seen from the solution space (Figures 18-21) that while each presents similar fluctuations, it follows the principle of nutrition and gradual decline. The producer population is the largest, while the number of lampreys and predators of primary consumers follows a gradual decline trend.

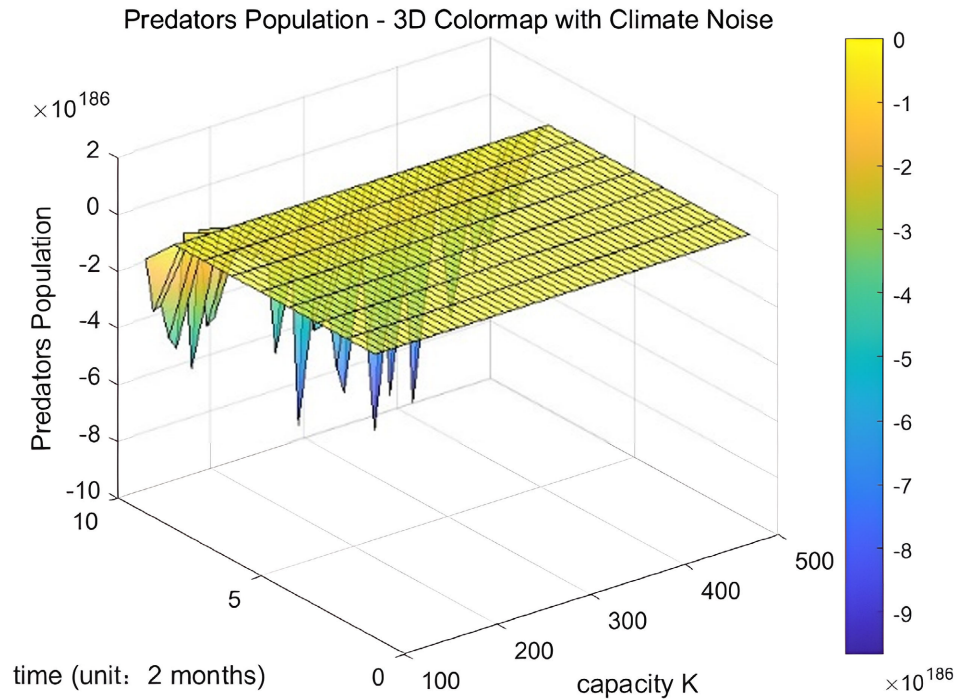


Figure 19. Predators' population-3D colormap with climate noise.

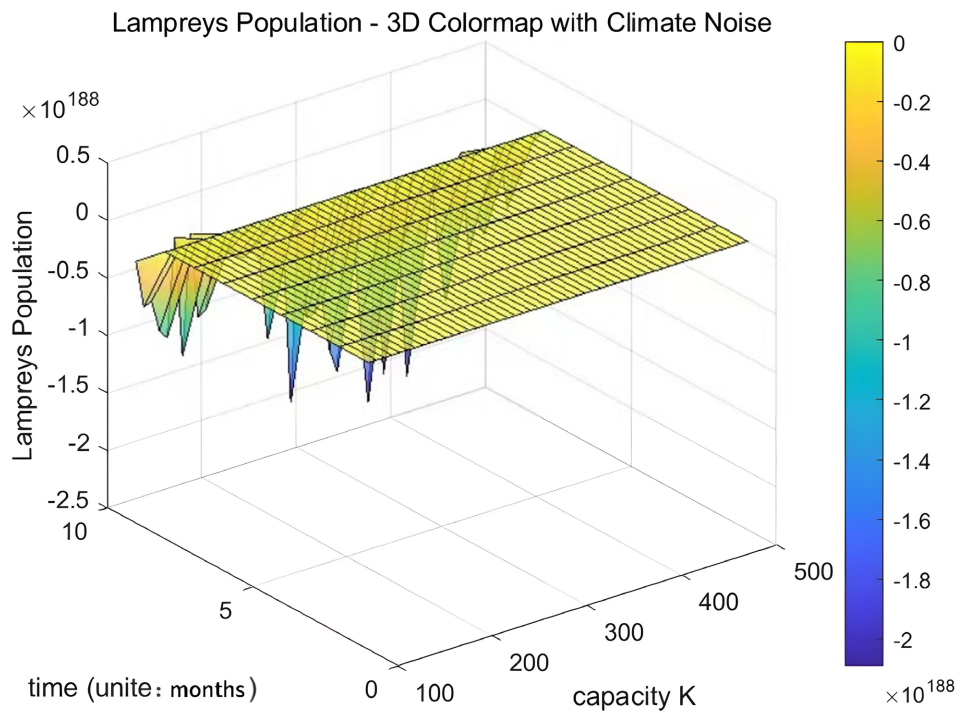


Figure 20. Lampreys' population-3D colormap with climate noise.

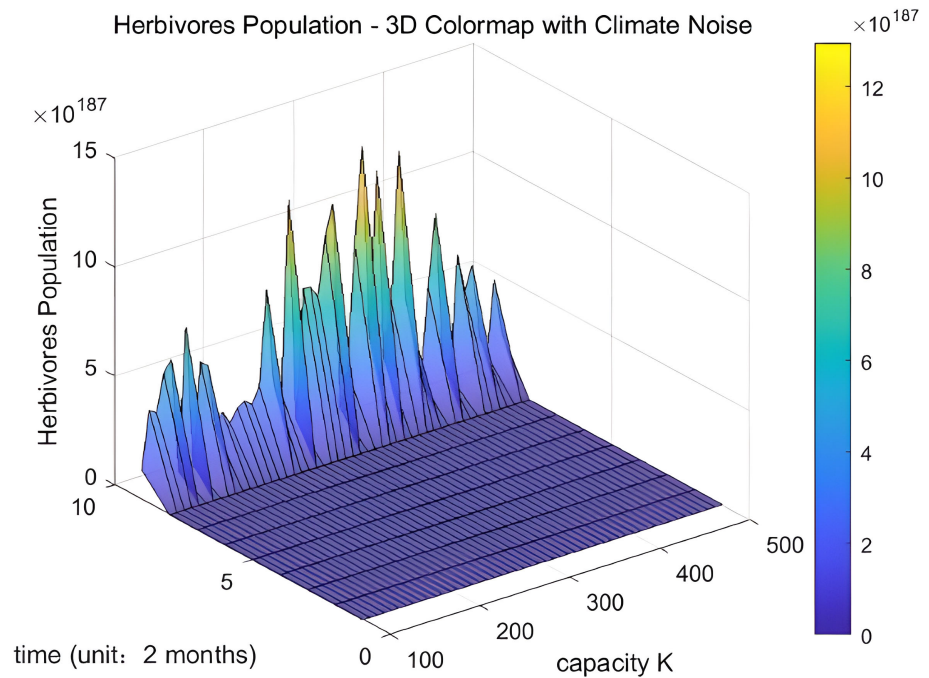


Figure 21. Herbivores population-3D colormap with climate noise.

6.3. Ecosystem Models and Food Web Models Simulate Integrated Biosphere Systems

In the natural biosphere, the ecosystem and the food web are often integrated, and the survival of the population is affected by the external impacts of the ecosystem and the internal adjustments of the food web. In the above, we have simulated an ecosystem through BP neural network. Beverton-Holt and logistic models were also used to simulate a simple food web. In order to more accurately reflect the impact of lampreys population on the overall ecosystem, the two models were integrated to form a complete biosphere system. In the main program, the code of the ecosystem model was called. The output value is used as the output of the food web model, the code of the food web model is called, the output of the ecosystem model is used as the input, and the output of the food web is obtained.

The specific process is the food web model using BP neural network to describe the interrelationships of different levels of the food chain, such as producers, herbivores and carnivores. The neural network receives the growth rate of the ecosystem as an input and outputs the number of populations at each level, and the growth rate of the ecosystem is used as an input to the food web model. Based on this input, the neural network predicts the populations of organisms at different levels. The food web model simulates changes in the number of producers, herbivores, and carnivores over time. These changes in quantity feed back into the ecosystem, forming a cycle through factors such as food supply and growth rate; The integration process is to bring the parameters of the Beverton-Holt and logistic differential equations in the food web into the hidden layer of the neural network in the ecosystem. The hidden layer composed of neurons

composed of multiple variables is the bridge connecting the food web and the ecosystem, just like in the whole biosphere. The connection between ecosystems and food webs is achieved through complex relationships of organisms' interactions, energy transfer, food chains and niches in ecosystems, which together constitute the structure and function of ecosystems, reflecting the interdependence and influence of organisms in their natural environment.

In the ecosystem model part of the total model, the change of food supply is simulated by sinusoidal function. The natural growth rate of the ecosystem is obtained by multiplying the food supply at the present time with the growth rate parameter.

6.4. Solution of the Global Biosphere Model

Changes in the number of producers and primary consumers are simulated using the Beverton-Holt model in the Food network model section, which is essentially a differential equation. However, in the operation, this differential equation is not explicitly analyzed, but the population number of each time period is gradually iteratively calculated by numerical simulation (Euler method). The Logistic model simulates the change in the number of secondary consumers, which is also simulated by numerical method.

Finally, three spatial surfaces (Figure 22, Figure 23) are obtained, which show the temporal evolution of the food supply in the ecosystem and the number of producers, primary consumers and secondary consumers at each level of the food chain.

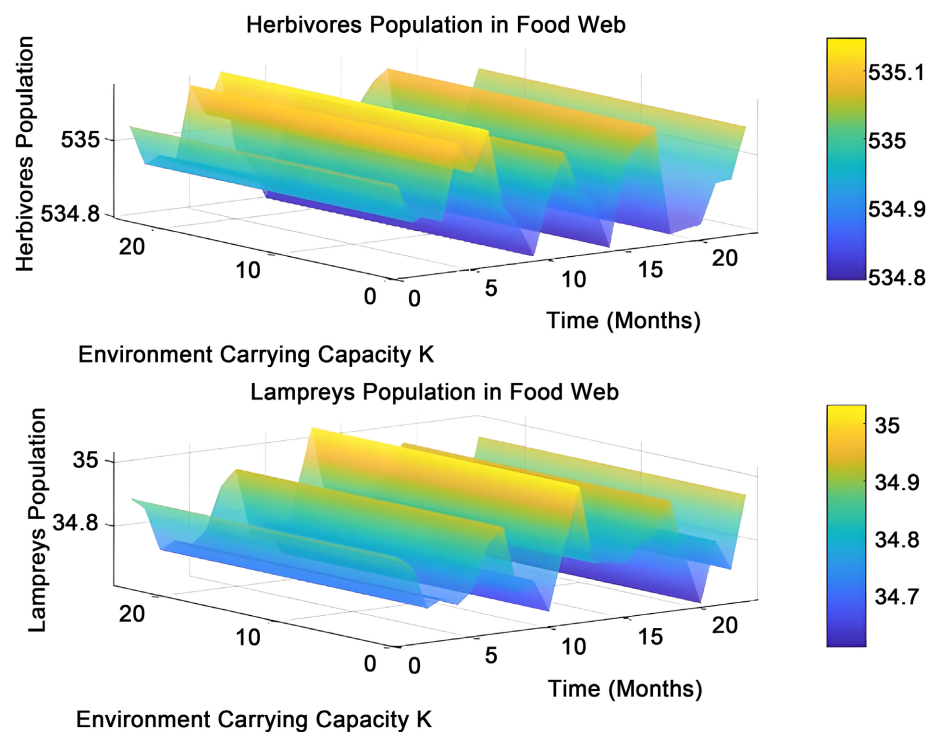


Figure 22. Herbivores and lampreys population in food web.

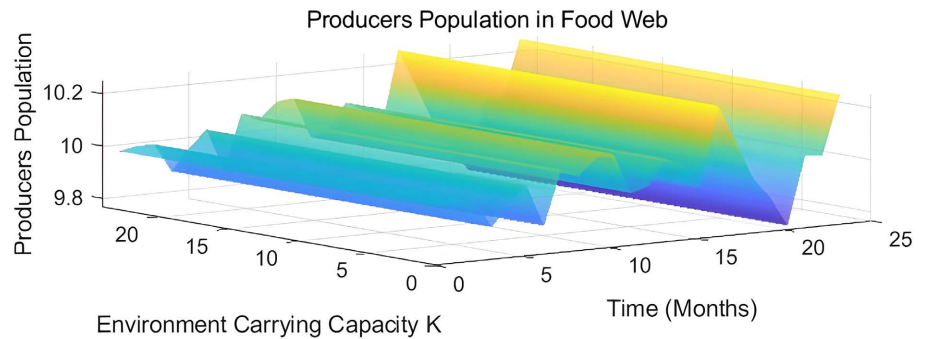


Figure 23. Producers’ population in food web.

Through the analysis of the curvature of different parts of the surface, it can be seen that the fluctuation of the number of lampreys is consistent with that of primary consumers and producers, and the peak value is slightly offset from the other two. Moreover, because the unit value of the quantity coordinate is small, the overall fluctuation range of lampreys is not large, indicating that lampreys have strong adaptability to the environment, but the fluctuation of primary consumers is obviously higher. Should be seriously affected by overpredation by lampreys.

6.5. Stochastic Forest Models Predict the Future Development of Ecosystems

In order to further predict the future evolution of each ecological niche in the future ecosystem, Euler method is used to approximate the surface (Table 3), and the numerical points on the multi-suite surface are obtained by Matlab calculation.

Using these data as training data to train the decision tree, the Lamprey variables contain the characteristics of the training decision tree, where the first column is time, the second column is the number of first-level consumer herbivore population, and the third column is the number of producer populations.

Table 3. The solution surface of the integrated model fits the data table.

	Initial quantity	Time step/month	Simulation time/month	2 months	4 months	...	24 months
The population of lampreys	35	1	24	34.8	34.9	...	34.7
Primary consumer population	535	1	24	534.9	534.8	...	534.8
Producer population	200	1	24	198.5	197.0	...	185.5

Random forest is composed of multiple decision trees to predict the number of three populations in the construction of the model (Figure 24), the decision tree uses the technology of random samples and random features to improve the generalization of the model. The new time points and the number of herbivore and producer populations are entered into each decision tree, and the prediction results for each decision tree are obtained.

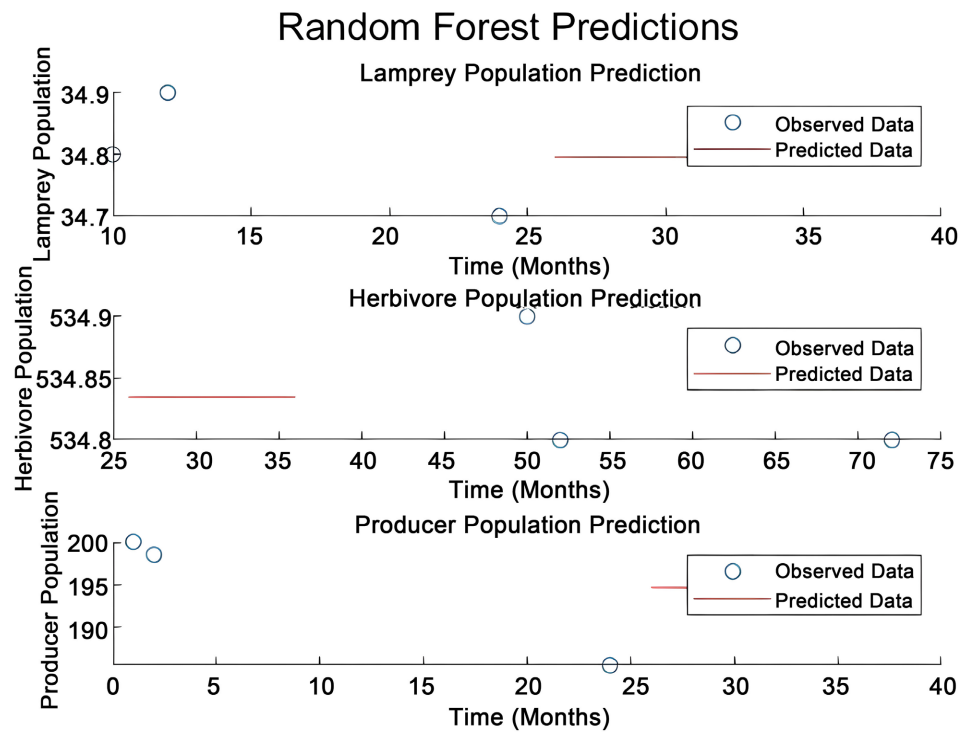


Figure 24. Forecast result.

Data analysis of random forest model operation results.

- Lampreys population: The number of lampreys in the future is predicted. There has been an increase in this amount, which may have an impact on the number of primary consumers and producers.
- Number of primary consumers: Lampreys are predators of primary consumers, and an increase in the number of lampreys may lead to a decrease in the number of primary consumers. This relationship is negatively correlated in the model.
- Number of producers: The number of producers may be affected by lampreys and primary consumers. If an increase in the number of lampreys leads to fewer primary consumers, it may reduce predation pressure on producers and thus affect the number of producers.

In summary, if the number of lampreys increases, it may have an impact on the dynamic balance of the entire ecosystem. Increasing the number of lampreys may result in a decline in the number of primary consumers and a relatively stable or rising number of producers. This can lead to changes in the food chain and ecological balance, which can have an impact on the stability of the entire ecosystem.

It can be seen that lampreys have a relatively serious impact on primary consumers, but have a positive effect on producers.

Finally, the parameter perturbation method is applied to the whole ecosystem model and decision tree prediction model, and the sensitivity of SHAP interpreter is tested and analyzed.

6.6. Result

- In summary, combined with other ecology and biology literature on lampreys [6], it is concluded that the changes in lampreys sex ratio have the following effects on ecosystem stability.
- Predation of other species: Lampreys have some stages of parasitic life that negatively affect their host fish. They can cause weakness in the host, affecting its survival and reproductive success.
- Ecological resource plunder: Lampreys, as top predators, will plunder a vast amount of ecological resources, including fish. This can cause an imbalance in the local food chain, leading to a decline in the number of other species, or even extinction.

7. Model IV: TOPSIS Hierarchical Analysis Model

In order to further study the impact of lampreys on the living environment of other populations, the impact weight of lampreys was defined through the investigation of the biomass of other species in the basin where lampreys lived, and the ratio of the biomass of each species to the total biomass. [7]

Fish: Mandarin fish, grass carp, carp, crucian carp, black carp.

Other niches: phytoplankton, benthic animals, aquatic bacteria.

The weight matrix evaluation of lampreys on the above objects is constructed.

$$\text{weight_ranges} = \begin{bmatrix} [0.2, 0.4] \\ [0.3, 0.5] \\ [0.1, 0.3] \\ [0.2, 0.4] \\ [0.3, 0.5] \\ [0.4, 0.6] \\ [0.3, 0.5] \\ [0.2, 0.4] \end{bmatrix} \quad (25)$$

Using TOPSIS comprehensive evaluation method of Matlab, the positive and negative approximation ideal solution vector and negative relative approximation degree of each species' influence on Lampreys were obtained.

The matrix was finally obtained to calculate the distance between positive and negative ideal solutions, and each species was sorted by relative proximity. The smaller the negative relative proximity, the more significantly the species was affected by Lampreys.

$$D \text{ to Ideal} = \sqrt{\sum_{i=1}^n (\omega_i - \omega_{ideal,i})^2} \quad (26)$$

$$D \text{ to Negative Ideal} = \sqrt{\sum_{i=1}^n (\omega_i - \omega_{neg-ideal,i})^2} \quad (27)$$

Relative proximity

$$\text{Relative Closeness} = \frac{D \text{ to Negative Ideal}}{D \text{ to Negative Ideal} + D \text{ to Ideal}} \quad (28)$$

The matrix was finally obtained to calculate the distance between positive and negative ideal solutions, and each species was sorted by relative proximity. The smaller the negative relative proximity, the more significantly the species was affected by Lampreys.

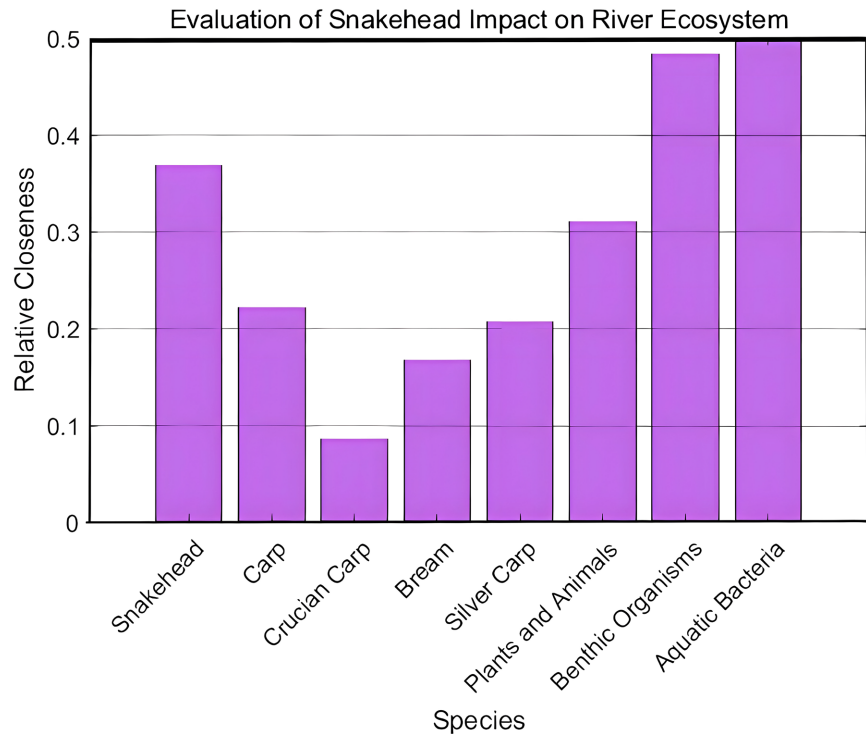


Figure 25. Evaluation of snakehead impact on river ecosystem.

From the above calculation results (Figure 25), it can be seen that grass carp, carp, crucian carp and black carp are greatly affected by lampreys, and it can be guessed that they are the main parasitic and predatory fish species of lampreys. Combined with the analysis of relevant ecological examples [8], it can be summarized that the effects of the change of sex ratio of lampreys on various organisms in the ecosystem and the advantages brought by the change are as follows:

- **Parasite environment:** Lampreys act as hosts for parasites at certain stages of their life cycle. If the sex ratio of lampreys changes, it may affect the availability and distribution of suitable hosts for the parasite. For example, if there are more lampreys of one sex, parasites that rely on that sex to complete their parasitic life cycle may benefit.
- **Population dynamics:** Variations in the sex ratio may affect the overall population dynamics of lampreys, and thus the number and population distribution of parasites that depend on lampreys to complete their life cycle.
- **Evolution of both parasitic relationships:** Variations in the sex ratio of lampreys populations may contribute to the ongoing co-evolutionary process

between lampreys and their parasites. This may lead to adaptive changes in parasite strategies and host resistance mechanisms, affecting the balance between host and parasite populations.

- **Increased parasitism:** Different sexes of lampreys may exhibit different immune characteristics, including the intensity and type of immune response. The parasite may adapt to these differences and select a more adaptable host sex to complete its parasitic life cycle more efficiently.
- **Improved reproductive success:** If the parasite has higher reproductive success on lampreys of a particular sex, changes in the sex ratio may have a positive effect on the reproductive ability of the parasite population. This can lead to an increase in parasite populations, affecting the entire parasite ecosystem.
- **Finding suitable hosts:** There may be behavioral differences between the sexes of lampreys, such as habitat selection and food preferences. These behavioral differences may provide the parasite with more options and opportunities, making it easier to find a host suitable for parasitism.

8. Sensitivity Analysis

8.1. Parametric Perturbation Method Is Used

The initial values of the population numbers of primary consumers, lampreys and predators, as well as the probability weights of predation rate, survival rate and fertility rate were disturbed. Then the influence on the prediction of the population numbers of lampreys was observed. The results of Matlab calculation showed that both models were stable. It also shows the stability of ecosystem and food web models and the reliability of experimental results in the first two problems.

8.2. Sensitivity Analysis of Local Interpretation

Using the SHAP interpreter, the SHAP values of each feature (time, number of primary consumer populations, number of producer populations) were calculated for the prediction of Lampreys population, so as to obtain the local importance of each feature. The results of matlab calculation are as follows.

The population size of primary consumers has a significant impact on the population prediction of lampreys, and the SHAP value also shows that this characteristic contributes a lot to the prediction. It can be concluded that primary consumers have an important impact on the population of lampreys in the ecosystem.

SHAP values for factors such as time, producer, etc. also provide the extent to which they have a relative impact on lampreys populations

Time: Time has a positive effect on the population of lampreys, and the time-related SHAP value in the model is positive.

The number of producers has a positive effect on the number of lampreys, and the SHAP value related to producers should be positive.

The results were analyzed with sensitivity analysis, parametric perturbation

method, SHAP interpreter-local interpretation sensitivity analysis, and the mutual sensitivity and positive and negative correlation among lampreys, primary consumers, and producers.

9. Model Evaluation

9.1. Strengths

Beverton-Holt model and Lotka-Volterra model: Both of which are specifically targeted at river biological populations and ecosystems, are more targeted for analyzing the impact of lampreys on ecosystems. The food web model established by combining the logistic equations in the form of differential equations can greatly improve the proximity between the analytic solution and the real situation, and Monte Carlo simulation can further solve the limitation of the differential equation to solve the over-complicated factors of the natural ecosystem, and use the statistical value to harmonise the final result.

Lotka-Volterra model and logistic model: Establish multiple time-dependent differential equation models, which can provide dynamic simulation of ecosystem evolution over time. By simulating the population dynamics of lampreys in ecosystems, it is possible to better understand their impact on the environment, especially over long-time scales. The differential equation model allows the introduction of ecological mechanisms to better understand the interactions between individual species and the stability of ecosystems.

BP neural network model: Simulation of ecosystem, because BP neural network is a nonlinear model, can adapt to complex ecosystem dynamics, and can capture the nonlinear relationship between various ecological factors. Learning and generalization ability, and the neural network adjusts the weight by learning historical data, so that it has certain learning and generalization ability, so that the model can predict the unknown data to a certain extent after training. Since ecosystems usually involve complex interactions between multiple variables, BP neural networks can flexibly handle multi-variable inputs and outputs, and are suitable for problems involving multiple ecological indicators.

9.2. Weaknesses

Our model initially simulated the ecosystem and food web. However, due to the extreme complexity of the natural ecosystem, with multiple random variables and system white noise, and due to the limitations of experimental data and time complexity, we failed to include too many factors, such as more complex climate factors, circulation between rivers and oceans, and migration of aquatic and coastal animals. Therefore, compared with the natural ecosystem, there are some limitations and errors in the analysis and prediction of the model.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Lin, B.B., Zhang, Z.P., Wang, Y.L. and Zhang, Y.Z. (2009) Advances in Genetic Diversity and Evolution of Lampreys. *Journal of Zoology Zhi*, **1**, 159-166.
- [2] Zhang, R. (2015) Synthesis of Cholic Acid Derivatives of Sex Pheromone of Sea Lampreys. Master's Thesis, Jiangxi Agricultural University.
- [3] <https://cn.bing.com/images>
- [4] McLaughlin, R.L., Hallett, A., Pratt, T.C., et al. (2007) Research to Guide Use of Barriers, Traps, and Fishways to Control Sea Lamprey. *Journal of Great Lakes Research*, **33**, 7-19. [https://doi.org/10.3394/0380-1330\(2007\)33\[7:RTGUOB\]2.0.CO;2](https://doi.org/10.3394/0380-1330(2007)33[7:RTGUOB]2.0.CO;2)
- [5] Lennon, R.E. (1954) Feeding Mechanism of the Sea Lamprey and Its Effect on Host Fishes. *Fishery Bulletin of the Fish and Wildlife Service*, **56**, 247-293.
- [6] Applegate, V.C. (1950) Natural History of the Sea Lamprey (Petromyzon Marinus) in Michigan. University of Michigan Press.
- [7] Lawrie, A.H. (1970) The Sea Lamprey in the Great Lakes. *Transactions of the American Fisheries Society*, **99**, 766-775. [https://doi.org/10.1577/1548-8659\(1970\)99<766:TSLITG>2.0.CO;2](https://doi.org/10.1577/1548-8659(1970)99<766:TSLITG>2.0.CO;2)
- [8] Siefkes, M.J., Johnson, N.S. and Muir, A.M. (2021) A Renewed Philosophy about Supplemental Sea Lamprey Controls. *Journal of Great Lakes Research*, **47**, S742-S752. <https://doi.org/10.1016/j.jglr.2021.03.013>