

Lampreys Ecosystem and Population Evolution in Multispecies Differential Equation Model

Summary

Lampreys inhabit marine and lacustrine ecosystems, playing a crucial role in the ecological food chain. Lamprey's unique ecological traits determine their sex ratio. This article primarily investigated the impact of the sex ratio of lampreys on the ecosystem.

To question 1, we designed a **laboratory ecosystem** based on the biological characteristics of lampreys. Then the **Multispecies Differential Equation Model** was established based on the **Lotka-Volterra model**. We assigned initial values to relevant parameters based on existing research and incorporated them into the Multispecies Differential Equation Model for simulation. We verified our model by **Cellular Automata (CA)**. Simulation data, by **NETLOGO**, revealed a **negative correlation** between food availability and the proportion of males. The dynamic sex ratio enhances the ecosystem's resistance to interference and contributes to its **greater stability**.

To question 2, we analyzed lamprey populations under three scenarios using simulated data from Question 1. We can find that revealed a significant **survival advantage** conferred by the sex ratio of lampreys, facilitating population reproduction. Nonetheless, in authentic natural environments, lamprey populations can proliferate rapidly, posing a potential risk of ecosystem collapse.

To question 3, we utilized simulated data to construct 3D graphs illustrating the relationship between the "time-sex ratio-population". Through examination of the **trajectory** and **direction field** of the differential equations within the **Multispecies Differential Equation Model**, we determined that an alternative sex ratio of lampreys contributes positively to ecosystem stability. Specifically, a higher proportion of male lampreys correlates with enhanced ecosystem resilience to interference.

To question 4, We introduced other parasites (competitors) and redesigned a **new Multispecies Differential Equation Model**. The data, by **NETLOGO**, demonstrate that when the lamprey sex ratio remains unchanged, the parasites will eventually become extinct. However, when the sex ratio changes, the number of parasites fluctuates within a certain range, indicating that the sex ratio provides advantages for the survival of the parasite.

Finally, we performed a sensitivity analysis on the initial population size of lampreys and discovered that if the initial value exceeds a certain critical point, the ecosystem collapses. Conversely, if the initial value falls below the normal range, the lamprey population faces extinction.

Keywords: The Lotka-Volterra Model, Differential Equations, Cellular Simulator, Sex Ratio

Contents

1	Introduction	2
1.1	Problem Background	2
1.2	Restatement of the Problem	2
1.3	Literature Review	3
1.4	Our Work	4
2	Assumptions and Justifications	5
3	Notations	6
4	The Multispecies Differential Equation Model	6
4.1	Model Description	7
4.2	The Establishment of This Model	7
5	Model Application and Results	8
5.1	Q1 The Impact of Alternate Sex Ratio on Larger Ecosystem	9
5.2	Q2 Lamprey Population's Advantages and Disadvantages	13
5.3	Q3 Impact of Sex Ratio on The Stability of The Ecosystem	14
5.4	Q4 Lamprey Offer Advantages to Others in The Ecosystem	16
6	Sensitivity Analysis	18
7	Model Evaluation and Further Discussion	19
7.1	Strengths	19
7.2	Weaknesses	19
7.3	Discussion	19
8	Conclusion	20
9	References	21
10	Appendices	22

1 Introduction

1.1 Problem Background

Lampreys are ancient organisms, and their sex-determination mechanism and sex ratio variation are determined by the availability of food in the environment, which is crucial for understanding biodiversity and ecological balance. When the male sex ratio is low, lampreys, as parasites, have a significant impact on the ecosystem, such as the proliferation of lampreys in the Great Lakes causing significant damage to the aquaculture of economically important fish such as salmon and trout. When the male sex ratio is high, lampreys can serve as a food source, and their presence is beneficial to the stability of the local ecosystem.

First, the sex determination mechanism of lampreys is very unique. Unlike most animals, their sex is not determined by genetic factors but is influenced by the external environment. In a food-abundant environment, lamprey larvae grow faster and are more likely to become female, while in a food-scarce environment, their growth slows down, making them more likely to become male. This adjustment of sex ratio is of great significance for lamprey populations to adapt to different environmental conditions.

Secondly, as part of the ecosystem, the sex ratio variation of lampreys has an impact on the entire ecosystem. Female lampreys are usually larger and better adapted to more stable environments, while males are more likely to survive in changing environments. Therefore, when the sex ratio of the lamprey population changes, it may affect their competition for food, reproductive success, and interactions with other organisms.

The sex ratio variation of lampreys not only affects their survival and reproduction but also has profound implications for the stability and dynamics of the entire ecosystem. Therefore, in-depth research and understanding of the sex ratio variation of lampreys and its ecological impact are of great theoretical and practical significance.

1.2 Restatement of the Problem

The lamprey can be divided into non-parasitic and parasitic types. The marine lamprey is parasitic, and its sex ratio can change according to changes in the external environment. The availability of food determines whether the larvae of the lamprey become male or female. The issue we are focusing on is the impact of changes in sex ratio on other organisms in the ecosystem and on the lamprey itself. We need to address the following questions:

- Question 1: Establish a population-based model to analyze the basic characteristics of the population evolution of the lamprey, and then consider the impact of changes in sex ratio on the ecological environment, i.e., the impact on the lamprey itself and other organisms in the ecosystem.
- Question 2: Combining the population model from question one, analyze the impact of food availability on the sex ratio of the lamprey, and identify the advantages and disadvantages of sex change characteristics for the development of the lamprey population.
- Question 3: Discuss the impact of changes in the sex ratio of the lamprey on other species, including food and predators, and analyze the stability of the ecosystem.

- Question 4: Expand the population model to consider adding other parasites as competitors of the lamprey, to analyze the impact of sex change in the lamprey on the competitors.

1.3 Literature Review

In recent years, changes in the sex ratio of lampreys, a primitive aquatic jawless vertebrate, and their impact on populations and ecosystems have become an important research topic in the fields of ecology and evolutionary biology. The sex ratio of lampreys varies greatly depending on species, population size, water area, and time of year, but is usually dominated by males ^[7].

Regarding factors that directly affect sex ratio, a key finding is that the sex of lampreys is not only genetically controlled but also directly determined by individual growth rate ^[8]. This suggests that growing conditions and resource availability may play important roles in sex determination, thereby affecting population structure and long-term survival strategies. In addition, the impact of environmental factors on sexual differentiation cannot be ignored. Research shows that the sexual differentiation of lampreys is directly affected by environmental conditions. The proportion of males in waters with relatively scarce resources has an absolute advantage, while the advantage of males in waters with relatively abundant resources is much weaker ^[5], which emphasizes the importance of the environment. Potential effects of changes on sex ratios and therefore population dynamics. Not only that, the male-to-female sex ratio of lampreys was also observed to be positively correlated with population size, with the larger the population, the greater the proportion of males. For the smallest population of 50-60, the male-to-female sex ratio is 1.2, while for a relative population of about 200, the highest sex ratio observed is 3.4, for a relative population of about 200 ^[6].

From an ecosystem perspective, lampreys have a significant impact on aquatic ecosystems. First, lampreys promote exchanges between water bodies through their life activities, adding a large number of nitrates while reducing the content of sulfates ^[1]. This chemical change has a profound impact on the nutrient cycle and chemical balance of the water ecosystem. Large amounts of nitrate may lead to eutrophication of the water body ^[12] and promote the growth of algae, and algal material is also the food of lamprey larvae. One of the sources, of this relationship can easily constitute positive feedback, which may be one of the reasons why lampreys are prone to flooding. Second, lamprey larvae can significantly increase the oxygen content of the river bed and the softness of the river through their digging activities ^[11], which is of great significance to the species diversity and ecological processes in the river ecosystem. The model we designed can play an important role in determining the number of adults and larvae believed to participate in the control of lampreys promptly. Third, most species of lamprey are parasitic, such as sea lamprey. Some patterns of sea lamprey marking on hosts suggest that when preferred hosts are scarce, selectivity for less preferred hosts increases and host survival is lower ^[2]. The presence of lampreys directly affects the reproduction of species in the lamprey's host organisms in the ecosystem.

Changes in the sex ratio of lampreys are not only affected by growth rate and environmental factors but also have potential impacts on population dynamics and ecosystem functions. Our model aims to digitize and visualize these effects and provide insights into

lamprey population characteristics, Life habits, artificial breeding, and control are all of great significance.

1.4 Our Work

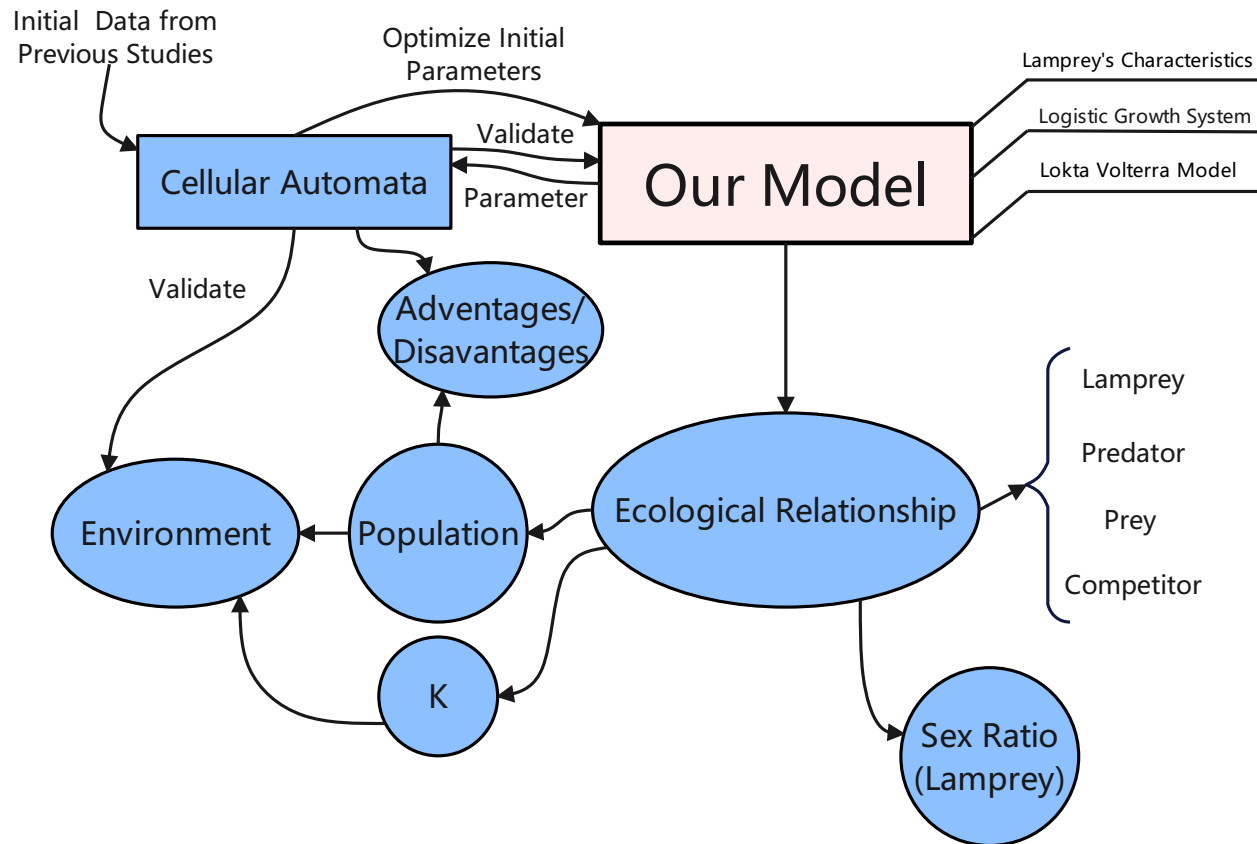


Figure 1: Our Work

To build a model that can reflect the interaction of consequences in the ecosystem, we established the LV-LG Lamprey Ecological Model. In our model, we set up the relationship between lamprey's predators, food, and organisms parasitized by the lamprey, and established a three-level consumer ecosystem model. We found suitable model parameters by searching for information to establish the initial state of the population and using MATLAB fitting methods. Since the essence of the Lokta Volterra model is the changing law of energy flow in the ecosystem, and considering the particularities of lamprey development and metamorphosis, we introduced more parameters to limit the lamprey population.

To analyze the impact of changes in the lamprey sex ratio on the ecosystem, we reviewed the literature to learn about the trend relationship between sex ratio and population size and made reasonable assumptions about the functional relationship between the two. Bring the lamprey population into our model and observe the changes in the population size and environmental capacity of other species affected by the lamprey. Lamprey population sizes were then mapped to sex ratios to obtain the effects of sex ratios on other organisms in the larger ecosystem. At the same time, we also analyzed the impact of the

corresponding population size of lampreys on abiotic factors in the ecological environment and the resulting interactions that reacted on biotic factors. To validate our model and hypotheses, we put our model into a CA (cellular automata) for simulation. Compare and analyze the obtained results with our model to obtain the rationality of our model.

To analyze the advantages and disadvantages of the lamprey population, we set different initial values for the parameters in the ecosystem model and conducted ecological simulations in CA. The changes in the population size and sex ratio of lampreys in different ecosystems were observed within the CA. At the same time, we plot in MATLAB the changes in population numbers affected by the sex ratio and compare them with those not influenced by the sex ratio for analysis. Furthermore, combining the results of the model from question one, we analyze the biological characteristics of lampreys and their impact on the population's advantages and disadvantages.

To analyze the impact of changes in lamprey sex ratio on ecosystem stability, we set the initial value of the model to a stable state, that is, a state where the differential equation is equal to 0, and put it into CA for simulation. Initially, it was assumed that changes in the sex ratio of lampreys had no effect, and population fluctuations of various species in the ecosystem were observed. Then introduce the impact of changes in lamprey sex ratio on the ecosystem obtained in the first question, and then observe the stability fluctuations of the ecosystem.

We use the impact of the lamprey's variable sex ratio simulated from CA on the ecosystem to compare and analyze it with other species in the ecosystem, such as the sources and quantities of resources required by parasites. Knowing whether lampreys' variable sex ratios could provide these species with an advantage.

2 Assumptions and Justifications

There are other assumptions.

- It is assumed that the immigration and emigration rates of various groups are zero. Similarly, in the artificially controlled long-term stable laboratory ecosystem, the immigration and emigration rates of various groups are also zero.
- The age structure of the lamprey population is assumed to be increasing due to their strong reproductive capabilities. The population has a higher number of juvenile individuals than adults or old individuals.
- It is assumed that the growth rate of biological populations, other than lampreys, is not affected by the sex ratio. Therefore, only lampreys in the ecosystem exhibit the characteristic of sex change. In nature, the male-to-male ratio of most organisms is approximately 1:1. Thus, changes in the sex ratio of other organisms can be disregarded when constructing a model.
- It is assumed that the impact of human hunting on lamprey populations is negligible. This article focuses on the impact of the lamprey sex conversion mechanism on the ecosystem, excluding any potential impact of human factors.
- It is assumed that the organisms in the model will not experience significant mortality due to force majeure or human factors. The possibility of earthquakes or human

errors causing the experimental environment to go out of control and resulting in mass mortality of the ecosystem's organisms is not considered.

- It is assumed that other species have reproductive cycles consistent with lampreys. To simplify the model, differences in reproductive cycles between species are ignored.
- Lampreys are assumed to be sexually differentiated at birth. The literature indicates that lampreys undergo a specific period of sexual differentiation, and changes in the environment, such as alterations in food availability, have a delayed impact on sexual differentiation. To expedite the results of sexual differentiation, we assumed that food availability has an instantaneous effect on the sexual differentiation of lampreys.

3 Notations

Symbols	Descriptions
$x_{1i}(t)$	population size of lampreys in the lamprey-specie i system
$x_i(t)$	population size of specie i in the lamprey-specie i system
r_i	natural growth rate of specie i in the lamprey-specie i system
r_{1i}	natural growth rate of lampreys in the lamprey-specie i system
K_i	carrying capacity of specie i in the lamprey-specie i system
K_{1i}	carrying capacity of lampreys in the lamprey-specie i system
q_f	proportion of males in the lamprey population
λ	survival rate of females in the lamprey population
α	impact coefficient of lampreys on host health
γ	predation intensity factor of male lampreys
φ	predation intensity factor of female lampreys
b_{ij}	effective contact rate between individual units of specie i and specie j
η_{ij}	competitive intensity of specie i on specie j

(*Note: $i, j = 1, 2, 3$. 1 lampreys, 2 preys, 3 predators, 4 other parasites)

4 The Multispecies Differential Equation Model

First, we designed a **laboratory ecosystem** based on the biological characteristics of lampreys. Subsequently, we established a model named the Multispecies Differential Equation Model based on the Lotka-Volterra model and ecological characteristics of lamprey. Then we analyzed the impact of changes in the sex ratio of lampreys on the ecosystem by our model and validated it with **CA(cellular automata)**. Furthermore, we found the advantages and disadvantages of changes in the sex ratio for the lamprey population and the stability of the ecosystem. Finally, we introduced parasites as competitors to the lampreys, to determine whether changes in the sex ratio of lampreys could offer advantages to other parasites.

4.1 Model Description

The impact of lampreys on the ecological environment is primarily manifested in their effects on other organisms. The impact of lamprey larvae on the environment is directly related to the population density and number of lampreys. Lampreys are both prey and parasites within the ecosystem. Considering the complex energy flow relationships in this ecosystem, we have established a lamprey ecological relationship model based on the Lotka-Volterra ecological system^[13] and the unique ecological relationships of lamprey (the Multispecies Differential Equation Model).

Our model incorporates tertiary consumers within the ecosystem of lampreys and quantifies the impact of the sex ratio within the parameters. Our model effectively represents the scenario of resulting interactions within the ecosystem.

4.2 The Establishment of This Model

Given the sex ratio of lampreys changes with the availability of food after their birth, and the population number $x_1(t)$ continuously varies over time. We represent the survival limit of lampreys living alone in this environment as K_1 .

Based on the principles of the logistic growth model^[3], we believe that factors slowing down the birth rate of lamprey populations should be reflected in the supply of host food, the number of predators capturing lampreys, and the sex ratio of lampreys, among other factors.

First, we consider the most basic scenario: the growth of the lamprey population under conditions influenced solely by resource factors. In such a case, the growth of the lamprey population should conform to the following equation:

$$\frac{dx_1}{dt} = r_1 x_1 \quad (1)$$

However, the right side of Equation 1 should include limiting factors due to the maximum environmental carrying capacity $\left(1 - \frac{x_1}{K_1}\right)$. We revise Equation 1 as follows:

$$\frac{dx_1}{dt} = r_1 \times \left(1 - \frac{x_1}{K_1}\right) \times x_1 \quad (2)$$

Furthermore, we also need to consider the impact of the sex ratio and survival rate of lampreys on their growth rate. Considering that changes in the sex ratio can affect the reproductive capacity and quality of lampreys, it is believed that there is a positive relationship between changes in the sex ratio and growth rate. Therefore, we revise Equation 2 as follows:

$$\frac{dx_1}{dt} = r_1 \times \left(1 - \frac{x_1}{K_1}\right) \times x_1 \times (1 - q_f) \times \lambda \quad (3)$$

Where q_f represents the proportion of males in the population, and λ indicates the survival rate of lampreys.

According to the literature^[8], we know that the proportion of males is influenced by population density, showing a positive correlation. Furthermore, the sex ratio ranges between 40% and 80%. We define the relationship between q_f and x_1 as follows:

$$q_f = 0.4 + \frac{0.4}{1 + e^{-\alpha p + \beta}} \quad (4)$$

Using MATLAB to fit data from the literature, we obtained $\alpha = 0.02$ and $\beta = 1.65$.

After taking into account the predation and parasitic relationships among organisms, we introduce the basic formula for the growth rates of host and predator populations. Based on previous assumptions, since the sex ratio in the growth rate formulas for other populations essentially follows a 1:1 ratio, the impact of the sex of other organisms on their growth rates is not considered.

$$\frac{dx_2}{dt} = r_2 \times \left(1 - \frac{x_2}{K_2}\right) \times x_2 \quad (5)$$

$$\frac{dx_3}{dt} = r_3 \times \left(1 - \frac{x_3}{K_3}\right) \times x_3 \quad (6)$$

Where x_2 is the function of the host population's change over time, r_2 is its natural growth rate, and K_2 is its survival limit number when living alone in the environment. x_3 is the function of the predator population's change over time, r_3 is its natural growth rate, and K_3 is its survival limit number when living alone in the environment.

Considering the predation or parasitic relationships among the three, we revise Equation 3, Equation 5, Equation 6 to:

$$\begin{cases} \frac{dx_1}{dt} = r_1 \times \left(1 - \frac{x_1}{K_1}\right) \times x_1 \times (1 - q_f) \times \lambda + Y \\ \frac{dx_2}{dt} = r_2 \times \left(1 - \frac{x_2}{K_2}\right) \times x_2 - b_{21}x_1x_2 \\ \frac{dx_3}{dt} = r_3 \times \left(1 - \frac{x_3}{K_3}\right) \times x_3 + b_{31}x_1x_3 \\ Y = \alpha x_1x_2b_{12} [q_f\gamma + (1 - q_f)\varphi] - b_{13}x_1x_3 [q_f\gamma + (1 - q_f)\varphi] \end{cases} \quad (7)$$

Where α represents the coefficient of the impact of lampreys on host health, γ represents the predation intensity factor of male lampreys, φ represents the predation intensity factor of female lampreys, b_{12} represents the effective contact rate between individual lampreys and individual hosts, b_{21} represents the effective contact rate between individual hosts and individual lampreys, b_{31} represents the effective contact rate between individual predators and individual lampreys, b_{13} represents the effective contact rate between individual lampreys and individual predators.

In Q4, we need to consider the impact of lampreys on more species within the ecosystem, such as other parasites. Lampreys, being parasitic as well, compete with these parasites, so it is necessary to introduce the competitive intensity η_{ij} between lampreys and other parasites, representing the competitive force of i on j . The relationship between their population numbers is reflected in Equation 8.

$$\begin{cases} \frac{dx_1}{dt} = r_1x_1 \left(1 - \frac{x_1}{K_1} - \eta_{41}\frac{x_4}{K_4}\right) \\ \frac{dx_4}{dt} = r_4x_4 \left[1 - \frac{x_4}{K_4} - \eta_{14}\frac{x_1}{K_1}q_f\varphi - \eta_{14}\frac{x_1}{K_1}(1 - q_f)\gamma\right] \end{cases} \quad (8)$$

5 Model Application and Results

Note: Lampreys are divided into parasitic and non-parasitic types. This article primarily refers to sea lampreys.

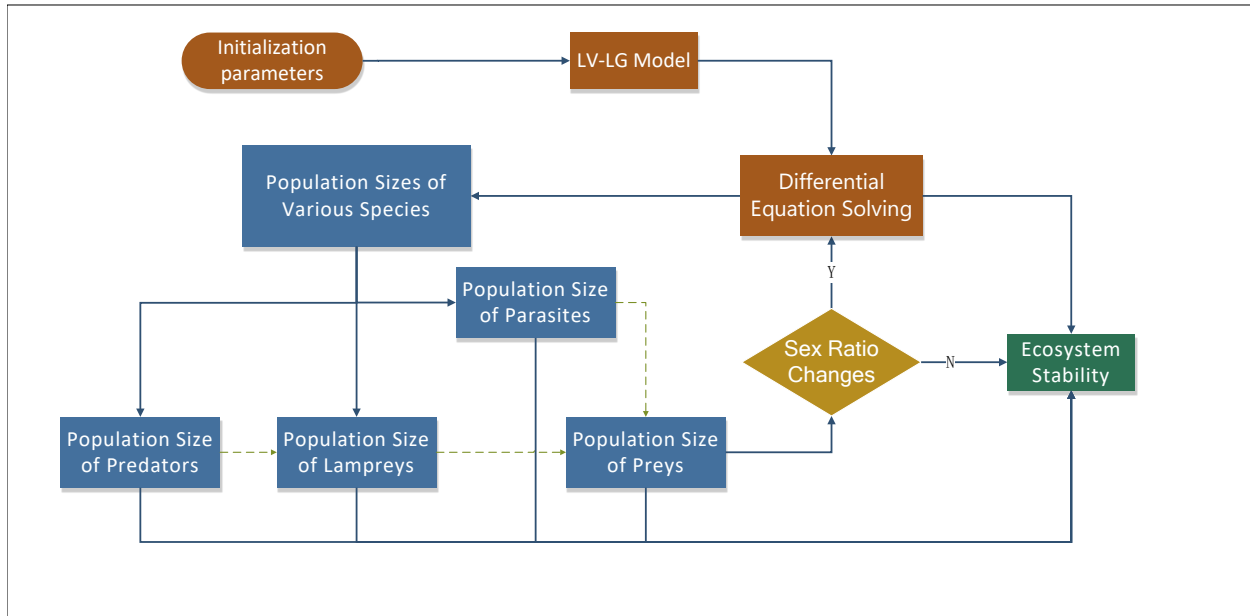


Figure 2: Our Model

5.1 Q1 The Impact of Alternate Sex Ratio on Larger Ecosystem

Under extreme conditions biased towards either a predominance of males or a scarcity of males, the maximum and minimum male-to-female sex ratios in the lamprey population are approximately 80% and 40%, respectively. Such extreme biases are unlikely to occur in normal ecosystems. We can reasonably hypothesize that the relationship between the lamprey population size and sex ratio within a certain range is an approximate S-shaped function curve. Fitting an S function requires two parameters α and β , as mentioned in the previous section. Recent studies have shown that, near the regression line, for the smallest population of 50-60, the sex ratio is 1.2, and the observed highest sex ratio is 3.4, corresponding to about 200 of the relevant population [6]. We use this data to fit the relationship function between the sex ratio and population size of lampreys.

In our laboratory ecosystem, we designed a food web and established a laboratory ecosystem as Figure 3. The prey within this system includes economically significant fish species such as bass, salmon, and trout. The predator specified as the lamprey refers exclusively to the sea lamprey. Due to the near absence of natural predators on the seabed, sea lampreys virtually act as demonic entities within their habitat. To simplify the topology of the food chain, we abstracted the natural predators of lampreys, such as humans and herons, into the "shark" predator depicted in Figure 3. It is important to note that actual images of the bass and heron^[4] were obtained from Wikipedia, the depiction of the lamprey is derived from [9], and the remainder of the illustration was generated using computer graphics. The placement of references is reserved for my academic manuscript.

Considering the food chain "prey-lamprey-predator", which we refer to as Food Chain 1, the sexual differentiation of lampreys is influenced by the availability of food. To analyze the impact of changes in prey population numbers on the proportion of male sea lampreys, we focus on the "prey-lamprey" segment of Food Chain 1.

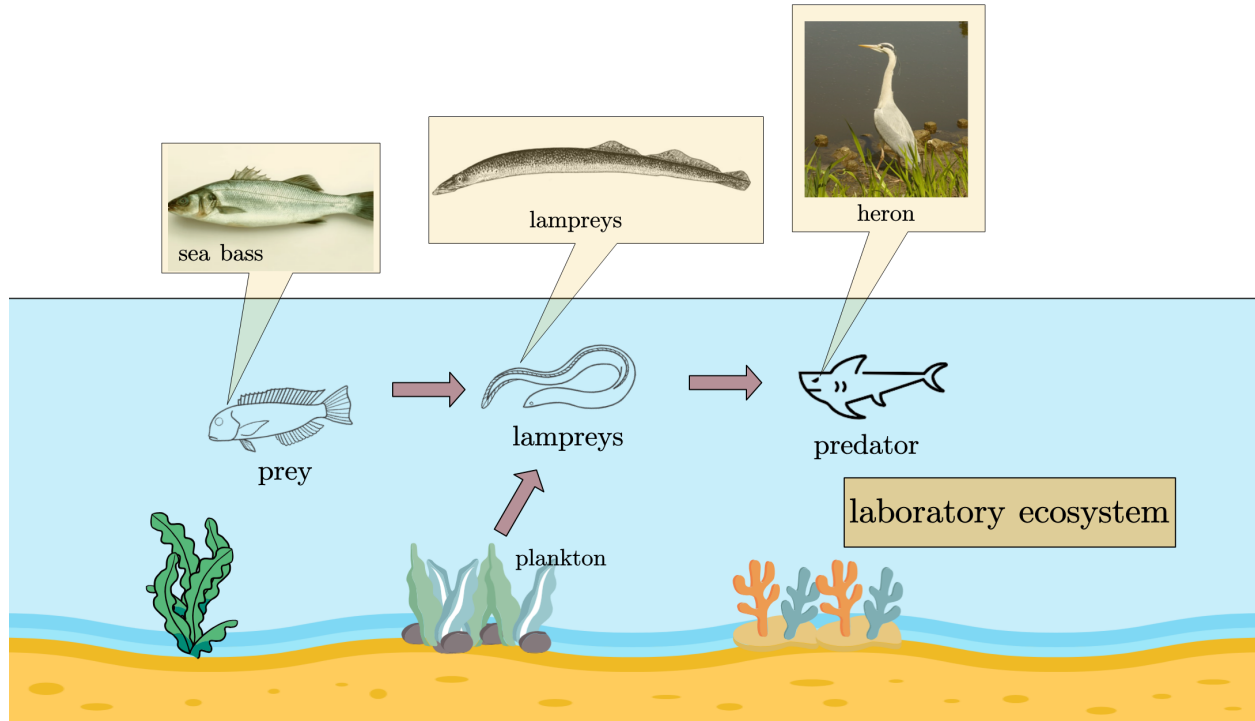


Figure 3: The Laboratory Ecosystem

By consulting previous literature for initial values of relevant parameters, we incorporate these initial values into the Multispecies Differential Equation Model, solve the differential equations, and obtain parameters suitable for our model:

$$\begin{cases} \frac{dx}{dt} = 0.0384x - 0.0003xy \\ \frac{dy}{dt} = -0.0244y + 0.0001xy \end{cases} \quad (9)$$

Afterward, we used CA(cellular automata) to simulate the changes over time in the population of producers (resources), food species, and the population of lamprey sharks in the laboratory ecosystem. The specific simulation data can be found in ?? (detailed results can be found in the appendix.).

parameter	value
initial-number-resource	500
initial-number-preys	400
initial-number-lampreys	100
resource-regrowth-time	5
threshold	50
preys-gain-from-food	5
lamprey-gain-from-resource	5
lamprey-gain-from-food	10

In the table, the first three parameters represent the initial quantities of producers, food species, and the population of lampreys (lamprey sharks), respectively. The fourth

parameter sets the energy acquisition ability of the producers to 5. The "Threshold" variable is used to indicate whether the survival strategy of lampreys changes. If the population of food species is less than the "Threshold" variable, then lampreys will become non-parasitic. Otherwise, they will continue to live as parasites.

The sixth variable represents the energy gained by an individual of the food species from one feeding event. Similarly, the seventh and eighth parameters represent the energy gained by an individual lamprey in non-parasitic and parasitic feeding events, respectively.

The reproductive capabilities of the prey and lamprey populations are represented by the ninth and tenth variables, respectively. The initialization image of the cellular automaton is as follows, where yellow represents the prey, and red represents the lampreys (for better observation of experimental phenomena, the size ratio of lampreys and their hosts is different from reality).

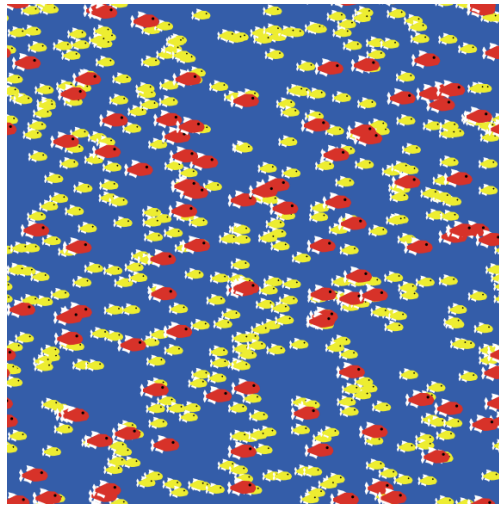


Figure 4: Prey and lamprey NETLOGO simulation diagram

The population dynamics of prey and lampreys (lamprey sharks) over time, simulated through CA, are depicted in Figure 4 (the NETLOGO interface is in Figure 19). In the graph, the yellow and red curves represent the populations of prey and lampreys, respectively. Both populations exhibit periodic fluctuations over time, with the prey population generally outnumbering the lamprey population. The lamprey population shows a proportional relationship with the prey population with a certain time lag, meaning that as the prey population increases, the lamprey population subsequently increases.

It can be observed that, for a certain period, the population of lampreys remains stable at its peak. Because during these times, lampreys are in a parasitic phase and are not preyed upon by any natural predators. This could lead to an overpopulation of lampreys, potentially causing an ecosystem collapse. To maintain the stability of our ecosystem, we have decided that when the population of lampreys exceeds 270, we will continue to intervene artificially to keep their population below 270, thus preserving the stability of the laboratory ecosystem. Data from the simulation is in the appendix Table 3 and Table 4.

This conclusion is different from Volterra's classical predator-prey dynamics, where reducing the prey population can lead to a decrease in the predator population^[13]. In the case of lampreys, the sex ratio can dynamically change. When the availability of food for lampreys decreases, they are more inclined to a non-parasitic lifestyle, which is more favorable for their survival. This dynamic behavior prevents mass deaths, species extinction, or ecosystem collapse from occurring, contrasting with the traditional predator-prey dynamics observed in Volterra's model.

To study the impact of changes in the sex ratio of lampreys on the ecosystem, we extracted the proportion "a" of male lampreys from the cellular automaton. We analyzed the relationship between the population quantities of prey (y1) and lampreys (y2), as well as the sex ratio "a" over time. The visual results are shown in Figure 5.

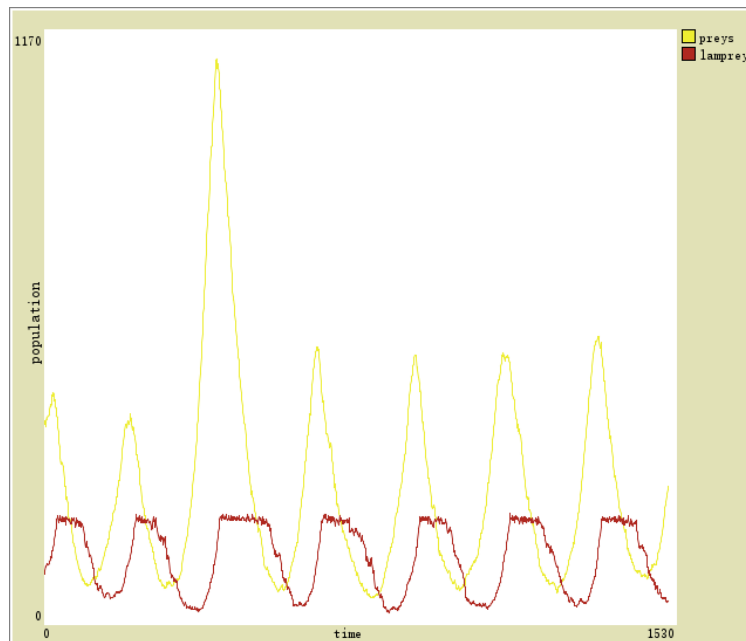


Figure 5: Preys and lampreys' population evolution

In the Figure 6, "y2" represents the available food quantity for lampreys. After a period of decline in "y2", the population of lampreys decreases, but the proportion of male lampreys increases. This indicates that when food resources become scarce, lampreys are more likely to differentiate into males. As the lamprey population decreases and the majority of lampreys choose a non-parasitic lifestyle, the prey population experiences relief and begins to recover.

When the lamprey population reaches a certain threshold, the availability of food for lampreys increases. At this point, the proportion of male lampreys decreases, and the female proportion increases, leading to an increase in the lamprey population. The sex ratio of lampreys causes fluctuations in the population of various species within a certain range, which is favorable for the stability of the ecosystem.

A particularly interesting finding is that the proportion of male lampreys generally falls within the range of 50%-80%, meaning that under normal circumstances, the number of males is equal to or greater than the number of females, consistent with the literature^[10].

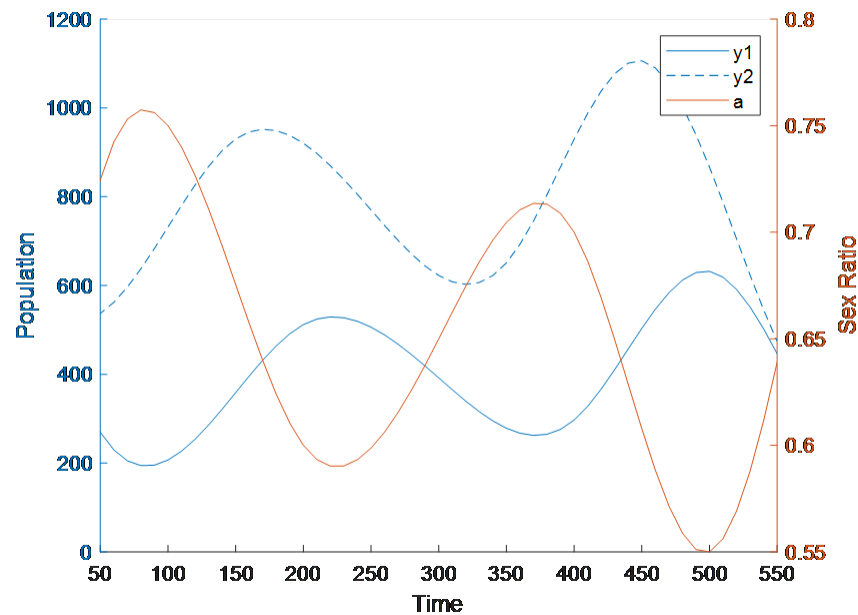


Figure 6: The relationship between the sex ratio of lampreys and the population

5.2 Q2 Lamprey Population's Advantages and Disadvantages

To illustrate the influence of sex ratios on the population dynamics of lampreys, we examine the effects of sex ratios on the lamprey population in two scenarios: "predator-lamprey" and "lamprey-predator." We set three different sex ratios, specifically low, medium, and high, within the range of [50%, 80%]. By using CA, we conducted simulations and processed the resulting experimental data for visualization. We analyzed the survival advantages and disadvantages of lampreys under different sex ratios.

In the local food chain "predator-lamprey", the population changes under three different sex ratios are shown in Figure 7. The solid line represents the population of lampreys, while the dashed line represents the population of the prey species.

Our analysis has found that a decrease in the male ratio leads to an increase in the population of lampreys, and concurrently, the number of prey species also increases. Additionally, it can be deduced from the graph that when the proportion of males increases, the cycle of population changes decreases. However, the populations of these species remain within a certain range, indicating the stability of the ecosystem. In other words, the sex ratio of lampreys is conducive to the survival of both lampreys themselves and their prey at the next higher trophic level. For lampreys, the dynamic changes in sex ratio prevent extinction due to food scarcity on one hand, and on the other hand, facilitate the recovery of other species populations, which is also beneficial for the survival of lampreys.

Unfortunately, in real-world settings, the populations of lampreys in certain areas are minimally affected by human intervention and natural predators. The dynamic changes in sex ratio endow this species with a strong capacity for survival, which can easily lead to lamprey proliferation becoming a nuisance. For instance, lampreys are found in large

numbers and are difficult to eradicate in places where commercial fish species are farmed, such as the Great Lakes, causing economic damage and environmental destruction to the local area.

Figure 8 represents the relationship between the sex ratio and population numbers in the "lamprey-predator" segment of the food chain. The solid line represents the number of lampreys, while the dashed line represents the number of food populations.

Analysis of Figure 8 reveals that an increase in the male ratio leads to a decrease in the populations of both lampreys and their predators. The cycle of population changes for both species is slightly reduced. However, the numbers of these populations remain within a certain range. Similarly, it can be inferred that the sex ratio of lampreys is conducive to the survival of both the lampreys themselves and other species, maintaining the balance of the food chain and contributing to the stability of the food chain's topological structure.

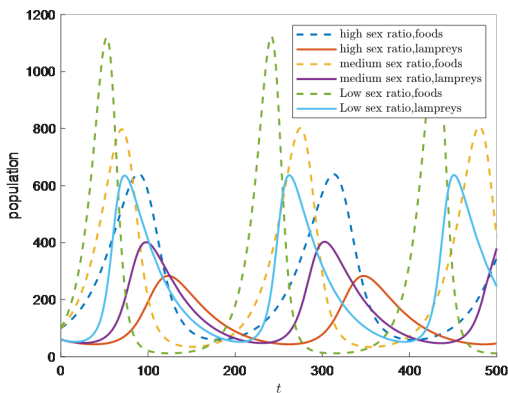


Figure 7: Population under different sex ratios in the "predator-lamprey" Food Chain

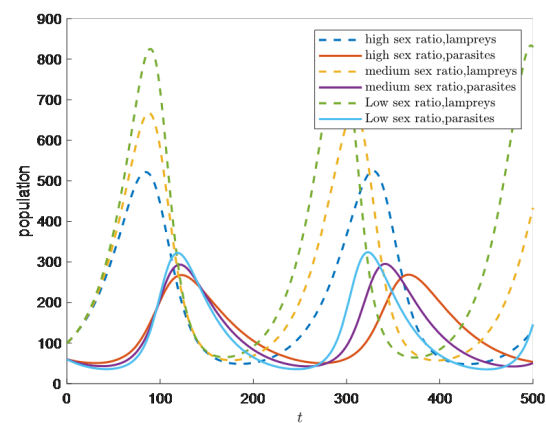


Figure 8: Population under different sex ratios in the "prey-lamprey" Food Chain

5.3 Q3 Impact of Sex Ratio on The Stability of The Ecosystem

Based on the solution to Q1, we can obtain the three-dimensional graphs and their two-dimensional views of "time-ratio-population" for both "prey-lamprey" and "lamprey-predator" as Figure 9.

The unit of the sex ratio in the two graphs above is ‰ (per mille). Through analysis, it has been found that 60%-70% is the optimal sex ratio range for lampreys, with sex ratios in this range being more conducive to the survival of lampreys.

Typically, in prey-predator models (also known as the predator-prey or Lotka-Volterra models), one of the conditions for the ecosystem to reach stability is when the rate of change of population numbers becomes zero, i.e., the derivative of the differential equation equals zero. This allows for the identification of population values at which the system stabilizes, known as equilibrium points or stable points. By analyzing the stability of these equilibrium points, it can be determined whether the system reaches a stable state around these points.

Trajectories and vector fields are utilized to visualize the changes in population num-

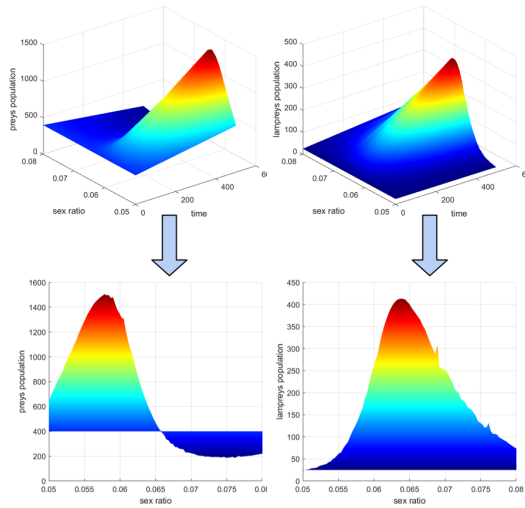


Figure 9: "prey-lamprey"

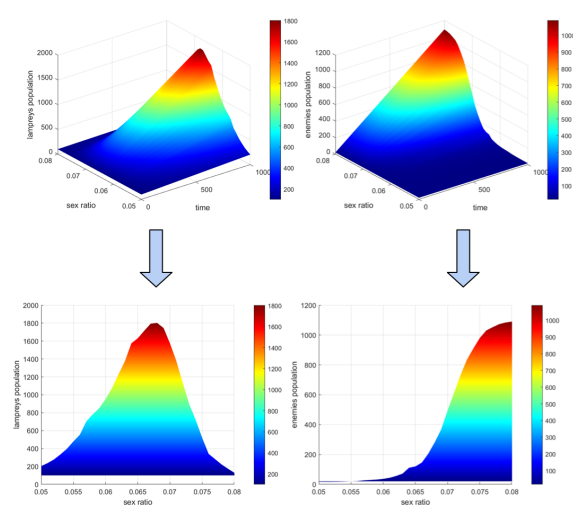


Figure 10: "lamprey-predator"

bers over time and the interactions between populations within the model. This aids in understanding the dynamic changes of the model as well as predicting the system's stability and limit behavior.

Vector fields describe the trend of change in population numbers in the phase space. In prey-predator models, vector fields show the direction of change for both prey and predator population numbers. By drawing vector fields, one can observe the trend of change in population numbers under different states and the stability of the system.

Trajectories are the path curves of population numbers changing over time, representing the change in different population numbers over time. Trajectories reveal how population numbers evolve over time, visually demonstrating the interactions and dynamic evolution between populations. Whether the trajectories form limit cycles indicates whether the population changes tend toward stability or exhibit periodicity.

The system can reach a stable state under the data conditions within a limit cycle. In population competition models, if the initial conditions of the system fall within a limit cycle, this is conducive to maintaining stability or trending towards stability in population numbers.

We have drawn the trajectories and vector fields for "prey-lamprey" (left) and "lamprey-predator" (right) as shown in the figure below. Figure 11 depicts the trajectories and vector fields under the conditions of a male ratio of 50%, 60%, and 65% (the vector fields of the three conditions differ slightly, with the vector field at a 65% sex ratio covering the previous two).

It can be observed that the larger the proportion of male lampreys, the larger the area covered by the limit cycle, indicating a stronger resilience of the ecosystem to disturbances. The dynamic changes in the sex ratio of lampreys cause the limit cycle to also dynamically change over time, and the ecosystem's resilience to disturbances changes continuously with the growth of the population. Therefore, the dynamic nature of the lamprey sex ratio is beneficial for the stability of the ecosystem. It is worth noting that the

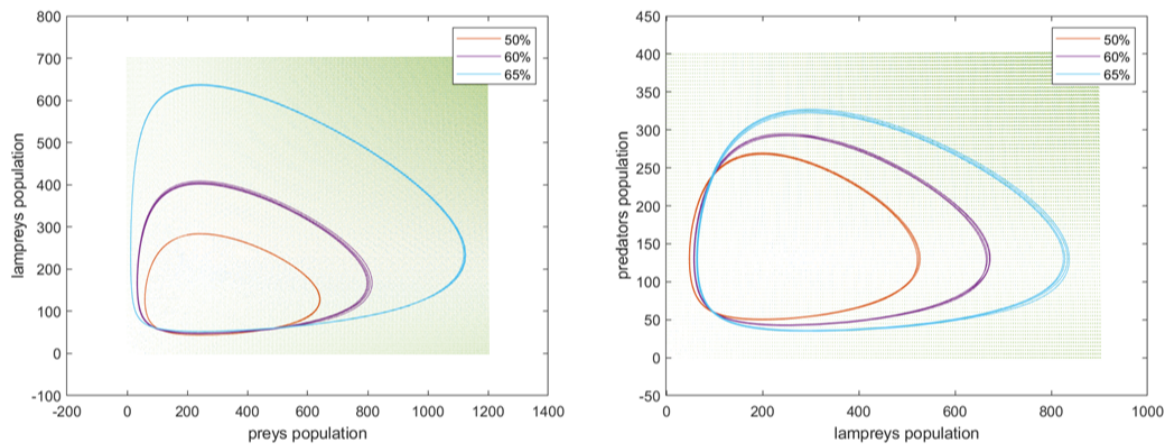


Figure 11: Trajectories and vector fields for "prey-lamprey" (left) and "lamprey-predator" (right)

initial values of the parameters in our model are derived from conclusions of previous studies, i.e., the parameters are set near the equilibrium point, which is why the model's trajectories can form a perfect closed loop.

Moreover, we find that a 65% sex ratio is optimal for lampreys in a laboratory ecosystem environment. At this sex ratio, the average population size of lampreys is the largest, and the laboratory ecosystem's resilience to disturbances is the strongest, with the best stability.

5.4 Q4 Lamprey Offer Advantages to Others in The Ecosystem

To analyze whether the change in the sex ratio of lampreys provides an advantage for other members of the ecosystem, we introduced parasites as competitors for lampreys in the food chain.

The parasites compete with lampreys for prey (prey), and the new laboratory ecosystem is as Figure 12.

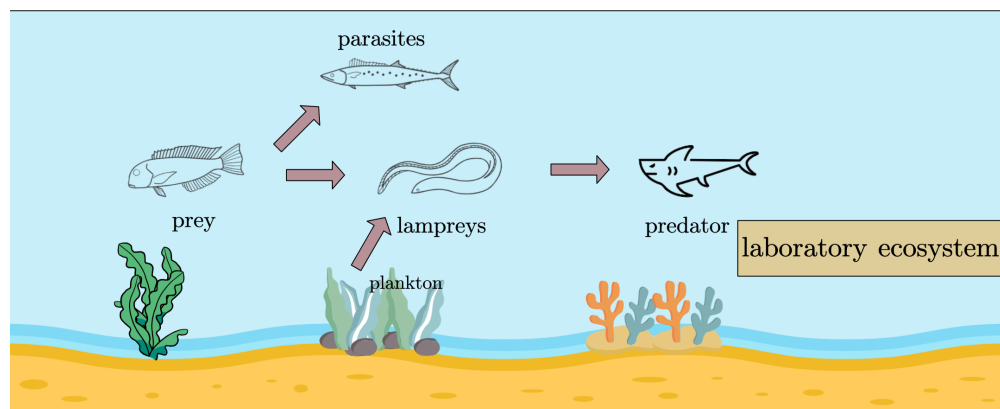


Figure 12: new Laboratory Ecosystem with competitors

We incorporated the new food web topology into the Multispecies Differential Equation Model to obtain new model parameters. Similar to the solution to Problem 1, we applied the model parameters to a cellular automaton to obtain simulation data for Food Chain 2 ("prey-parasite"). We considered the population dynamics of prey and parasites under two scenarios: when the sex ratio of lampreys is stable and when it changes. In the cellular automaton initialization image Figure 18, the orange represents prey, while the green represents parasites.

When the sex ratio of lampreys is stable, meaning that the competitors of parasites do not exhibit sex ratio changes, the simulation results for the populations of prey and parasites are as Figure 13.

In cases where the competitors of parasites do not exhibit sex ratio changes. Even when the availability of food for lampreys is low, lampreys will choose to parasitize. In the figure, it is shown that the number of parasites increases with the increase in the population size of prey. However, when the population of prey's next nutrient level (parasites and lampreys) also increases, the population of prey sharply decreases to extinction. Subsequently, parasites also face extinction due to the lack of a food source. At this point, if lampreys maintain a fixed sex ratio and continue to choose parasitic life, lampreys will also go extinct.

When lampreys exhibit sex ratio changes, the simulation results for the populations of prey and parasites are as Figure 14.

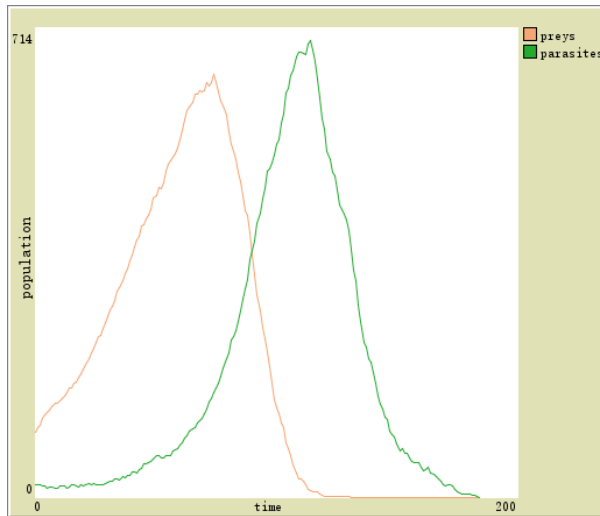


Figure 13: Simulation result without sex ratio changes

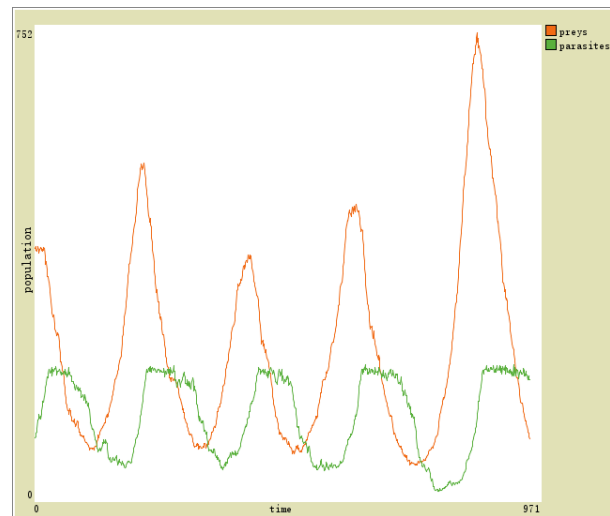


Figure 14: Simulation result with sex ratio changes

When lampreys choose non-parasitic life in the case of low food availability, the number of parasites gradually increases when the population of prey is sufficient to meet the needs of both parasites and lampreys. When the population of prey is insufficient, some lampreys choose non-parasitic life, reducing the predation pressure on prey, and allowing the population to recover. Due to the competitive impact of parasitic lampreys, the number of parasites will not continue to increase indefinitely; they will stabilize after reaching a certain value for a certain period. Because parasites are influenced by prey with a delay,

their population dynamics curve is similar to that of prey but with a certain time lag.

6 Sensitivity Analysis

In the process of solving Q1, we used cellular automata for simulation and found that the result of population evolution is related to the initial settings of the lamprey population. When the initial values of the prey and lamprey are set to 400:150, The population evolution diagram is shown below.

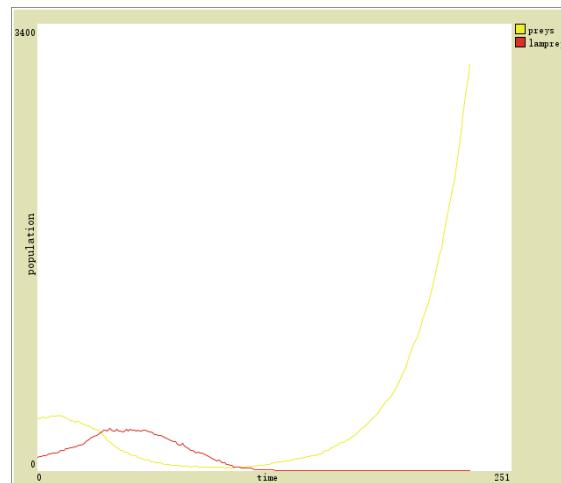


Figure 15: The population evolution graph when lamprey are set to 400:150

Figure 15 shows that, in cases where the initial number of lampreys is high, when food suddenly decreases, lampreys are unable to adjust their sex ratio in time due to the latency in sex differentiation. Not enough food is available, which leads to their extinction. Subsequently, the very few surviving prey experience exponential growth, with their numbers exceeding the carrying capacity of the environment, leading to ecosystem collapse.

When the initial values of the prey and lamprey are set to 400:105, the population evolution graph is Figure 16.

Figure 16 is similar to the results in Problem 1. With a reasonable initial setting for lampreys, the numbers of both prey and lampreys fluctuate within a certain range, indicating stability in the ecosystem.

When the initial values of the prey and lamprey are set to 400:50, the population evolution graph is Figure 17

Although the lampreys do not become extinct in the Figure 17, the number of prey sharply increases after a certain critical point, almost exhibiting exponential growth. This is found to be because the initial value of lampreys is relatively small, and their maximum value exceeds a threshold that would trigger human intervention, whereas prey is not subject to artificial fishing. Due to the variability in the sex ratio of lampreys, there is a slight gap in the reproductive capacity between lampreys and prey in each cycle. Over time, this gap gradually increases, and when it exceeds a certain critical point, the number of prey skyrockets to the point that it exceeds the carrying capacity of the laboratory ecosystem, leading to ecosystem collapse.

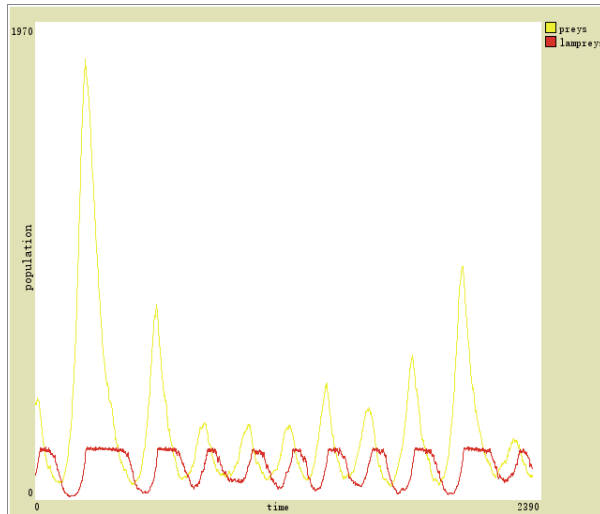


Figure 16: The population evolution graph when lamprey are set to 400:105

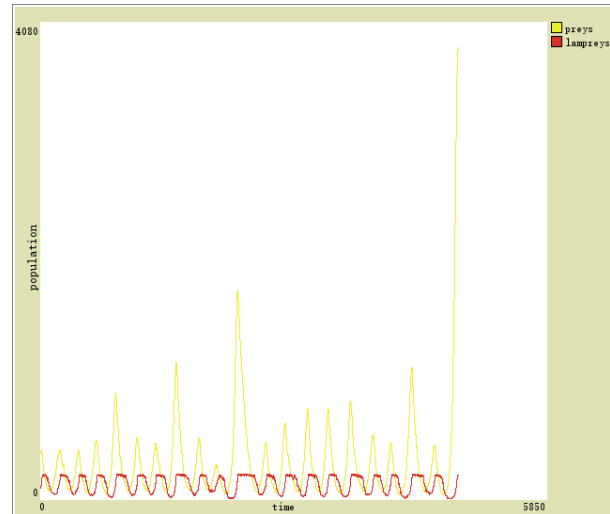


Figure 17: The population evolution graph when lamprey are set to 400:50

7 Model Evaluation and Further Discussion

7.1 Strengths

Throughout the modeling process, we established reasonable assumptions, which facilitated the construction and solution of the model. We developed an adaptive model, which accurately demonstrates the population dynamics of lampreys, the prey, and the predators based on changes in environmental resources and the sex ratio of lampreys. The simulation running through CA (cellular automata) not only validated the model but also offered a more intuitive reflection of the interactions among various groups.

It is convenient to add more competitors, predators, or prey types to our model. By adjusting the parameters of the differential equations, the model can simulate the interaction trends among biological populations under different environmental conditions, enhancing the model's extensibility.

The inclusion of a coefficient for the impact of parasites on host health in our model, different from the predator-prey relationship, makes the model more accurate.

7.2 Weaknesses

Our model contains many parameters, and the initial values were obtained through extensive research, thus introducing potential errors. These parameter values are related to biology. Due to the complexity and diversity of biological entities, the values of these parameters may vary, affecting the outcomes of our model.

7.3 Discussion

In our model, we assume that sex differentiation in lampreys is determined at birth. While the reproductive cycles of other organisms in the ecosystem follow the same pattern as lampreys. If there is a need to address delays or different reproductive cycles, relevant functions can be added to simulate specific reproductive cycle models.

We explore the impact of lamprey sex determination mechanisms on both other organisms in the ecosystem and lampreys. Our model provides more effective ways for spe-

cialists in the relevant field to understand the dynamic changes in lamprey populations, better predict and control the potential threats posed by the invasive species, and formulate appropriate management strategies. Our model can also be used to delve deeper into how to restore ecosystems damaged by lampreys, considering the contribution of lampreys to the stability of the ecosystem.

Furthermore, the sex ratio of lampreys has the potential to impact the transmission of other pathogens or parasites within the ecosystem. This attribute can be leveraged to formulate preventative strategies against other pathogens or parasites.

Our model encompasses both the beneficial and detrimental aspects of lampreys in the ecosystem. By setting different initial values for lamprey populations in the model, we can simulate whether lampreys have a positive or negative impact on the ecosystem.

Combining our model with environmental change models facilitates the prediction of the evolution of sex determination mechanisms and ecosystem responses under different ecological pressures. Since our model utilizes CA(cellular automata) for visual simulation, it can be considered for educational and awareness purposes. Dynamic demonstrations can be used to enhance public understanding of lampreys or similar species, raising awareness and understanding of ecosystem conservation.

8 Conclusion

In addressing the issue of gender ratio changes in lampreys and their impact on ecological environments and population evolution, we employ a combination of biological methods, differential equations, and cellular automata techniques. The influence of gender ratios on ecosystems is described using the Multispecies Differential Equation Model, where differential equations are solved based on predefined parameters, and simulations and validations are conducted using cellular automata. Our simulation results contribute to enhancing the resilience of ecosystems to disturbances and aid in the management and control of lampreys in economic zones to maximize profits from commercial fish species. Sensitivity analysis reveals that many parameters in our model rely on initial values from previous studies, potentially introducing flaws. Therefore, setting initial values for lampreys based on existing research and conclusions is crucial. Additionally, by incorporating aspects such as reproductive cycles, pathogen transmission, and dynamic demonstrations, we pinpoint areas to enhance the completeness of our model. Ecosystems serve as the cornerstone of Earth's life and a repository of diversity, presenting numerous mysteries awaiting exploration. Following this paper, we intend to delve deeper into other characteristics of lampreys, such as their medicinal value, to better promote economic development and resource utilization.

9 References

- [1] Carolin Boeker and Juergen Geist. "Lampreys as ecosystem engineers: burrows of *Eudontomyzon* sp. and their impact on physical, chemical, and microbial properties in freshwater substrates". In: *Hydrobiologia* 777 (2016), pp. 171–181.
- [2] Gavin C Christie and Chris I Goddard. "Sea Lamprey International Symposium (SLIS II): advances in the integrated management of sea lamprey in the Great Lakes". In: *Journal of Great Lakes Research* 29 (2003), pp. 1–14.
- [3] Aaron James Clark, Larry Wayne Lake, and Tadeusz Wiktor Patzek. "Production forecasting with logistic growth models". In: *SPE Annual Technical Conference and Exhibition?* SPE. 2011, SPE–144790.
- [4] Wikipedia contributors. *Heron*. Accessed 5-February-2024. 2024.
- [5] Margaret F Docker and F William H Beamish. "Age, growth, and sex ratio among populations of least brook lamprey, *Lampetra aepyptera*, larvae: an argument for environmental sex determination". In: *Women in ichthyology: an anthology in honour of ET, Ro and Genie* (1994), pp. 191–205.
- [6] MW Hardisty. "Sex composition of lamprey populations". In: *Nature* 191.4793 (1961), pp. 1116–1117.
- [7] Nicholas S Johnson, Tyler J Buchinger, and Weiming Li. "Reproductive ecology of lampreys". In: *Lampreys: Biology, Conservation and Control: Volume 1* (2015), pp. 265–303.
- [8] Nicholas S Johnson, William D Swink, and Travis O Brenden. "Field study suggests that sex determination in sea lamprey is directly influenced by larval growth rate". In: *Proceedings of the Royal Society B: Biological Sciences* 284.1851 (2017), p. 20170262.
- [9] R Nieuwenhuys et al. "Lampreys, petromyzontoidea". In: *The Central Nervous System of Vertebrates: Volume 1/Volume 2/Volume 3* (1998), pp. 397–495.
- [10] Ian C Potter et al. "The taxonomy, phylogeny, and distribution of lampreys". In: *Lampreys: biology, conservation and control: volume 1* (2015), pp. 35–73.
- [11] Hokuto Shirakawa, Seiji Yanai, and Akira Goto. "Lamprey larvae as ecosystem engineers: physical and geochemical impact on the streambed by their burrowing behavior". In: *Hydrobiologia* 701 (2013), pp. 313–322.
- [12] Val H Smith, Samantha B Joye, and Robert W Howarth. "Eutrophication of freshwater and marine ecosystems". In: *Limnology and oceanography* 51.1part2 (2006), pp. 351–355.
- [13] Yasuhiro Takeuchi. *Global dynamical properties of Lotka-Volterra systems*. World Scientific, 1996.

10 Appendices

Table 3: Population of lampreys and preys over time

time	preys	lampreys	time	preys	lampreys	time	preys	lampreys
1	400	100	40	329	203	79	119	206
2	401	102	41	323	206	80	117	190
3	404	105	42	318	207	81	112	198
4	406	106	43	307	211	82	106	206
5	402	107	44	299	198	83	104	197
6	408	109	45	288	199	84	100	195
7	415	113	46	276	203	85	106	192
8	418	118	47	269	207	86	106	195
9	422	120	48	266	211	87	104	189
10	430	125	49	263	205	88	103	192
11	429	131	50	252	202	89	101	192
12	426	129	51	251	210	90	103	190
13	422	132	52	250	204	91	103	181
14	425	136	53	243	206	92	97	180
15	425	139	54	230	209	93	98	169
16	428	145	55	223	208	94	94	166
17	432	150	56	211	206	95	93	164
18	429	154	57	206	205	96	98	168
19	429	156	58	203	205	97	101	168
20	432	165	59	197	195	98	99	158
21	431	170	60	189	194	99	105	152
22	430	169	61	187	188	100	103	155
23	431	172	62	180	194	101	106	154
24	426	187	63	180	193	102	104	144
25	429	193	64	183	209	103	107	139
26	414	200	65	183	203	104	106	137
27	407	208	66	179	212	105	102	131
28	410	212	67	176	202	106	102	126
29	406	207	68	170	211	107	101	122
30	393	203	69	158	206	108	101	124
31	383	205	70	148	208	109	103	116
32	376	210	71	146	196	110	106	117
33	369	210	72	137	205	111	105	117
34	368	204	73	136	204	112	106	122
35	357	216	74	131	190	113	107	122
36	350	208	75	128	190	114	106	122
37	346	208	76	126	196	115	102	118
38	342	197	77	127	194	116	104	111

39	339	207	78	124	197	117	105	106
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Table 4: Population of lampreys and predators over time

time	lampreys	predators	time	lampreys	predators	time	lampreys	predators
1	100	60	40	229	62	79	391	125
2	106	61	41	230	64	80	398	127
3	107	64	42	235	64	81	401	135
4	106	65	43	239	67	82	394	144
5	109	68	44	238	63	83	390	148
6	109	73	45	239	63	84	393	159
7	110	74	46	240	61	85	393	165
8	113	74	47	243	62	86	386	170
9	119	75	48	242	62	87	390	174
10	122	79	49	240	65	88	398	177
11	125	80	50	241	65	89	388	181
12	129	78	51	251	67	90	373	178
13	131	78	52	263	70	91	374	184
14	133	79	53	266	70	92	363	190
15	137	80	54	275	72	93	355	198
16	138	79	55	279	72	94	362	201
17	136	76	56	280	76	95	360	207
18	140	76	57	294	77	96	351	206
19	144	75	58	294	79	97	357	206
20	143	75	59	299	79	98	339	203
21	146	70	60	309	78	99	332	207
22	148	67	61	316	78	100	327	206
23	156	68	62	326	80	101	324	212
24	158	66	63	338	83	102	311	210
25	162	65	64	344	87	103	305	210
26	164	62	65	351	87	104	289	205
27	169	66	66	359	96	105	273	196
28	171	66	67	362	94	106	273	200
29	178	67	68	367	93	107	269	207
30	180	68	69	366	97	108	266	210
31	183	67	70	360	99	109	269	209
32	193	57	71	366	105	110	257	207
33	201	57	72	375	111	111	247	206
34	208	55	73	373	113	112	251	213
35	212	53	74	380	112	113	255	208
36	219	56	75	385	115	114	250	204

37	223	59	76	384	118	115	241	200
38	226	60	77	386	119	116	233	209
39	231	61	78	385	121	117	228	202

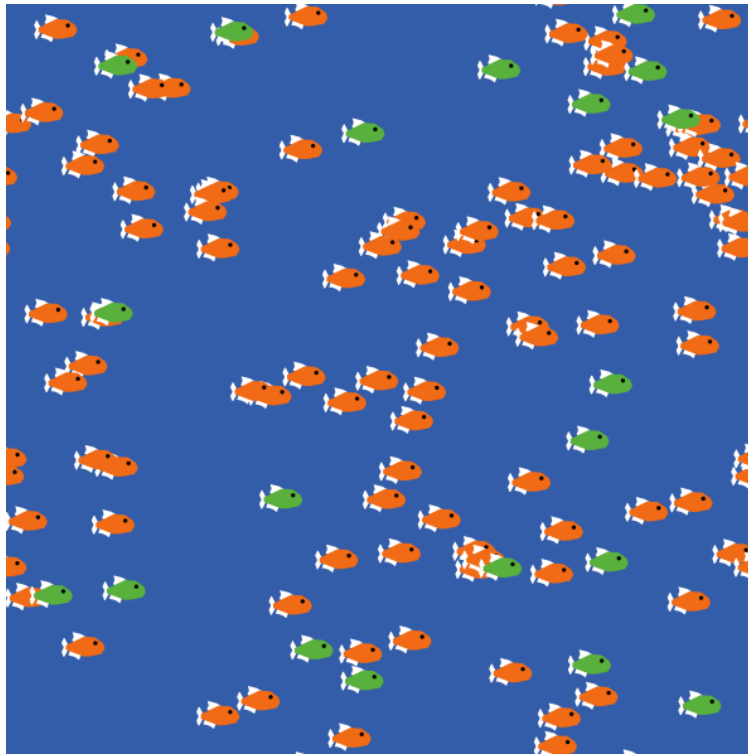


Figure 18: Cellular Automata initialization image

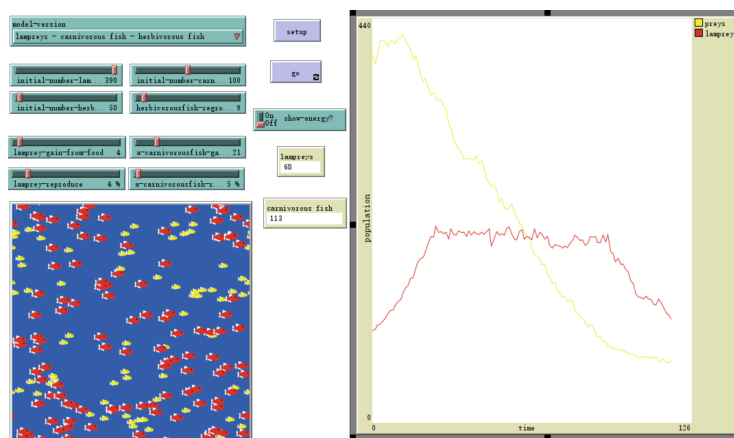


Figure 19: NETLOGO interface

AI Usage Report

1. OpenAI ChatGPT (Feb 3, 2024 version, ChatGPT-3.5,)

Query1: Incorrect use of surf Z must be a matrix, not a scalar or vector.

Output: Sorry, I noticed an error. We should make sure that the input to the 'surf' function is in matrix form, but currently 'cell2mat' returns a vector, not a matrix. Let's correct this problem:

```

""matlab
clc, clear, close all;
% Define the right-hand term of the system of
differential equations
a_vvalues = 0.02 : 0.01 : 0.08; %thevaluerangeofa
dxy = @(t, z, a) [a*z(1)-0.0003*z(1)*z(2);
-0.024*z(2)+0.0001*z(1)*z(2)] ;
% Use ode45 to solve the system of differential equations, and specify the initial condition
as (70,40) and the time range from 0 to 100.
tspan = [0, 100];
z0 = [70; 40];
x_vvalues = zeros(length(a_vvalues), length(tspan));
y_vvalues = zeros(length(a_vvalues), length(tspan));
for i = 1:length(a_vvalues)
a = a_vvalues(i);
sol = ode45(@(t, z) dxy(t, z, a), tspan, z0);
x_vvalues(i, :) = deval(sol, tspan, 1);
y_vvalues(i, :) = deval(sol, tspan, 2);
end
% Draw the three-dimensional graph of x(t)
figure;
surf(tspan, a_vvalues, x_vvalues);
xlabel('Time t', 'Interpreter', 'Latex');
ylabel('Parameter a', 'Interpreter', 'Latex');
zlabel('x(t)', 'Interpreter', 'Latex');
figure;
surf(tspan, a_vvalues, y_vvalues);
xlabel('Time t', 'Interpreter', 'Latex');
ylabel('Parameter a', 'Interpreter', 'Latex');
zlabel('y(t)', 'Interpreter', 'Latex'); ""
Here I am using pre-allocated matrices
'x_vvalues' and 'y_vvalues' and then populating these matrices in a loop.
Finally, I use these matrices as input to the 'surf' function.

```

2. OpenAI ChatGPT (Feb 4, 2024 version, ChatGPT-3.5,)

Query1: Convert the citations of the following two websites into BibTex format:

Wikipedia contributors. Heron— Wikipedia, the free encyclopedia, 2024. [Online; accessed 5-February-2024].

The Independent. Sea Bass: the Superstar of the Seas. Retrieved 2017-12-02.

Output: Here is an example of converting these two website quotes into BibTeX format:

```
""bibtex
```

```
@onlinewikipediaheron,
author = Wikipedia contributors,
title = Heron,
year = 2024,
url = https://en.wikipedia.org/wiki/Heron,
note = Accessed 5-February-2024,
@articleindependentseabass,
author = The Independent,
title = Sea Bass: the Superstar of the Seas,
year = 2017,
url = https://www.independent.co.uk/life-
style/food-and-drink/sea-bass-the-superstar-of-
the-seas-a8082971.html,
note = Retrieved 2017-12-02,
""
```

Here, the first reference is to Wikipedia's Heron page, using the '@online' type. The second reference is to the Independent article, using the '@article' type.

3. OpenAI ChatGPT (Feb 4, 2024 version, ChatGPT-3.5,)

Query1: English Academic Revision: The ecosystem's anti-interference ability is enhanced and it has strong stability.

Output: The ecosystem exhibits enhanced resilience to disturbances and demonstrates robust stability.

4. OpenAI ChatGPT (Feb 5, 2024 version, ChatGPT-3.5,)

Query1: English academic revision: The dynamic sex ratio makes the ecosystem more resistant to interference and has greater stability.

Output: The dynamic sex ratio enhances the ecosystem's resistance to interference and contributes to its greater stability.

5. OpenAI ChatGPT (Feb 5, 2024 version, ChatGPT-3.5,)

Query1: English academic revision: We used the simulation data of Question 1 to analyze the lamprey population under three conditions of low, medium and high sex ratios, and found that in the laboratory ecosystem, the sex ratio of lampreys makes lampreys powerful. survival advantage. But In real natural environments, lampreys can easily become overrun and even cause ecosystem collapse.

Output: We utilized the simulation data from Question 1 to examine the lamprey population across three scenarios characterized by low, medium, and high sex ratios. We observed that within laboratory ecosystems, the sex ratio of lampreys confers a significant survival advantage. However, in authentic natural environments, lamprey populations can swiftly escalate and potentially precipitate ecosystem collapse.

6. OpenAI ChatGPT (Feb 5, 2024 version, ChatGPT-3.5,)

Query1: English academic revision: We used simulated data from Question 1 to examine lamprey populations under three scenarios characterized by low, medium, and high sex ratios. We observed that the sex ratio of lampreys has a significant survival advantage and is conducive to the reproduction of the population. However, in a real natural environment, lamprey populations can increase rapidly and potentially lead to ecosystem collapse.

Output: We analyzed lamprey populations under three scenarios—low, medium, and high sex ratios—using simulated data from Question 1. Our observations revealed a significant survival advantage conferred by the sex ratio of lampreys, facilitating population reproduction. Nonetheless, in authentic natural environments, lamprey populations can proliferate rapidly, posing a potential risk of ecosystem collapse.

7. OpenAI ChatGPT (Feb 5, 2024 version, ChatGPT-3.5,)

Query 1: English academic revision: To question 3, based on the simulation data, we created 3D graphs of the "time-sex ratio-population", finding that 60%-70% is the optimal sex ratio range for lampreys. By the trajectory and direction field of the differential equations in the Multispecies Differential Equation Model, we can find that the alternative sex ratio of lamprey benefits ecosystem stability. The greater the proportion of male lampreys, the stronger the ecosystem's ability to resist interference.

Output: In response to question 3, utilizing simulation data, we constructed 3D graphs illustrating the "time-sex ratio-population" relationship. Our analysis revealed that the optimal sex ratio range for lampreys falls between 60% and 70%. Moreover, through examination of the trajectory and direction field of the differential equations within the Multispecies Differential Equation Model, we determined that an alternative sex ratio of lampreys contributes positively to ecosystem stability. Specifically, a higher proportion of male lampreys correlates with enhanced ecosystem resilience to interference.