The Mystery Hidden in the Sex Ratio

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Abstract. In order to unravel the secrets hidden within the gender ratio of lampreys, we proposed several models to simulate the cascade of effects on ecosystems. Firstly, we established a Logistic model-based food chain model. We found that as the gender ratio increases, the predator population rises while environmental resource levels decline, and the lamprey population initially increases before decreasing. Simultaneously, habitat utilization rate was considered as an indicator affecting the ecosystem. Through modeling, we discovered a positive correlation between habitat utilization rate and the gender ratio of lampreys. Secondly, we developed a Game Evolution Model based on the Moran process. We defined a payoff matrix to simulate competition between male and female lampreys. We assumed that gender ratio and environmental resource levels influence reproductive success, finding that an intermediate gender ratio results in higher reproductive success, considered an advantage. When the gender ratio approaches 0 or 1, reproductive success decreases, considered a disadvantage. We also defined a function for resource utilization rate concerning gender ratio, concluding that higher gender ratios lead to higher resource utilization rates.Thirdly, we defined an ecosystem evolution model based on the Logistic model. Three interaction modes between organisms and lampreys were established: competition, independent coexistence, and parasitism. We discovered that when the gender ratio approaches 0.64, the stability of the ecosystem is highest.Through entropy weight method, we determined the weights of each factor, and observed the stability of the comprehensive index at different gender ratios, finding that a gender ratio closer to 0.64 corresponds to a more stable ecosystem. Finally, utilizing the previously established game evolution model, we introduced parasites. In this model, by reducing the punishment for parasites choosing betrayal and increasing the probability of parasites choosing betrayal. Ultimately, we found that deviating from a gender ratio of 0.64 provides an advantage for parasites.

Keywords: Logistic Model; Evolutionary Game Model; Payoff matrix; Gender ratio.

1. Introduction

1.1. Background

The lamprey is a type of jawless fish with a long evolutionary history and a unique life cycle.[1] Parasitic in nature, lampreys attach themselves to other fish using their suckerlike mouths, feeding on the blood and tissues of their hosts. Lampreys possess the ability to manipulate their sex ratio, allowing them to adjust the proportion of males and females in their population based on environmental conditions. The sex ratio of lampreys not only influences their own population dynamics but also has broader impacts on the ecosystem.[2]



Figure 1: A lamprey in the deep sea

Within the ecosystem, lampreys occupy a complex food chain,which is shown in Figure 3.[3] Parasites in the environment not only infest lampreys but also compete with them. Additionally, small fish and shrimp prey on lampreys, while simultaneously serving as hosts for both lampreys and parasites. These smaller organisms, in turn, become prey for larger fish.

1.2. Restatement of the Problem

• How does the ability of lampreys to manipulate their sex ratio affect the broader ecological system?

• What benefits and drawbacks does the ability of lampreys to control their sex ratio bring to their population?

• How does the fluctuation in lamprey sex ratios influence the overall stability of the ecosystem?

• Could an ecosystem characterized by fluctuating sex ratios in the lamprey population provide benefits to other organisms within the ecosystem, particularly parasites?

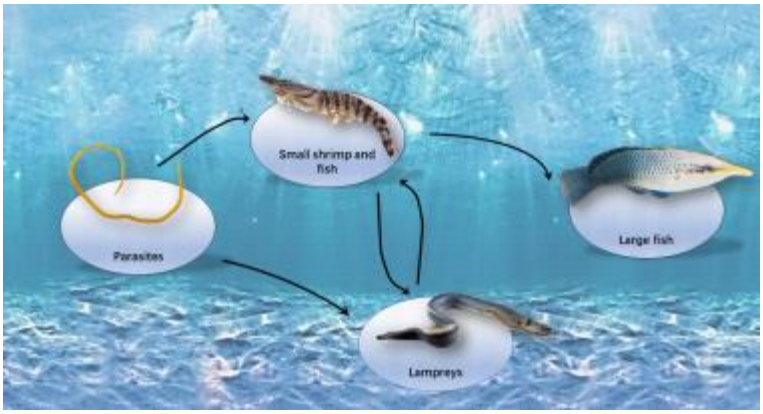


Figure 2: Complex Food Chain

1.3. Our Work

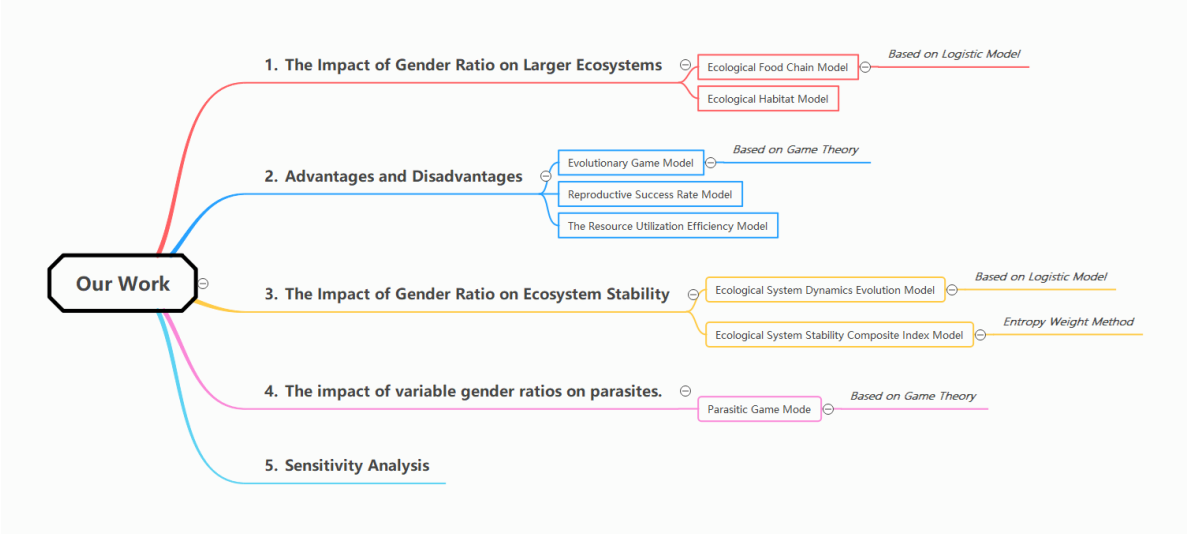


Figure 3: Our Work

2. Assumptions

• Assuming that the change in the gender ratio of lampreys is a gradual process, not subject to sudden and drastic fluctuations over a short period, it can be described by a system of differential equations.

• Assuming that the environmental carrying capacity remains relatively stable and does not undergo significant changes over a short period.

• Assuming that the change in the gender ratio of lampreys is solely influenced by the availability of resources, disregarding other potential factors such as temperature, light,water flow, and genetics.

• Assuming that the impact of the gender ratio change in lampreys on the ecosystem is primarily manifested through their interactions with other species, such as predation, being preyed upon, competition, symbiosis, etc. This can be represented using a food web model to depict their role and position within the ecosystem.

• Assuming that the gender ratio of lampreys is a continuous variable, it can be represented by a function. The independent variable of this function is the availability of resources, referring to the quantity and quality of food and space in the environment.

• Assuming that the change in the gender ratio of lampreys has a long-term cumulative effect on the ecosystem and does not yield significant results over a short period, stability analysis can be employed to assess its impact and risks on the ecosystem.

3. List of Notation

Table 1: Notation and Variables Used in the Model

Symbols	Description
$N_{lamprey}$	the population size of the lamprey species
$N_{predator}$	he population size of predators
$N_{resource}$	the quantity of environmental resources
R_{sex}	the number of male lampreys divided by the total lamprey population
$S_{reproduction}$	the reproductive success rate
$R_{resource}$	he environmental resource utilization rate
K	carrying capacity of the environmental resources
$R_{reproduction}$	the habitat occupancy rate
$C_{habitat}$	habitat capacity

4. List of Notation

4.1. The Impact of Gender Ratio in Lamprey on Larger Ecosystems

4.1.1 Ecological Food Chain Model

In ecology, understanding the interactions between populations is crucial for understanding the dynamics of the whole ecosystem. Lampreys are one of the key species in the ecosystem, whose sex ratio may have significant effects on the population dynamics and ecosystem stability. Our team's research aims to explore the potential impacts of lamprey sex ratio on the larger ecosystem by developing differential equation models.

Our team's research proposed a differential equation model to explore the impact of lamprey's sex ratio on the larger ecosystem. The impact indicators are as follows:

• the number of predators

• the number of lampreys

• the amount of environmental resources

By adjusting the model parameters, we simulated the dynamic evolution of lamprey population, predator population, and environmental resources, and studied the impact of sex ratio on these ecological indicators.

Without considering the presence of predators and the influence of environmental resource levels, the Logistic model of idealized population growth for a single species of lamprey is represented by Formula 1.

$$\frac{dN_{\text{lamprey}}}{dt} = r \cdot N_{\text{lamprey}} \cdot \left(1 - \frac{N_{\text{lamprey}}}{K}\right) \tag{1}$$

In this Formula, Nlamprey is the population size of the lamprey species, r represents the natural growth rate of lampreys and K is the carrying capacity of the environmental resources.When considering interspecific relationships, it is necessary to introduce a correction term, as shown in Formula 2.

$$\frac{dN_{\text{lamprey}}}{dt} = r \cdot N_{\text{lamprey}} \cdot \left(1 - \frac{N_{\text{lamprey}}}{K}\right) - h \cdot N_{\text{predator}} \cdot N_{\text{lamprey}} \tag{2}$$

In this Formula,where h represents the predation rate and Npredatoris the population size of predators, this correction term reflects the inhibitory effect of predator's predation behavior on the population size of lampreys.

So, how does the population size of predators change? We have formulated Formula 3.

$$\frac{dN_{\text{predator}}}{dt} = h \cdot N_{\text{predator}} \cdot N_{\text{lamprey}} - \gamma \cdot N_{\text{resource}} \cdot N_{\text{predator}} \tag{3}$$

In the Formula, Nresource represents the quantity of environmental resources. γ represents the index of the natural death rate of predators, and due to the constraints of environmental resources, it may indirectly affect the natural death rate. Therefore, we multiply γ by both Nlamprey and Npredator.

Next, we have defined a differential equation regarding the quantity of environmental resources,as shown in Formula 4.

$$\frac{dN_{\text{resource}}}{dt} = -d \cdot N_{\text{resource}} + f \cdot N_{\text{predator}} \cdot N_{\text{lamprey}} \tag{4}$$

In the Formula, d represents the natural depletion rate of environmental resources,and f represents the competitive impact between predators and resources.

The population size of lampreys, the population size of predators, the quantity of environmental resources, and the gender ratio of lampreys are all interconnected, leading us to the pivotal set of differential equations,as shown in Formula 5.

$$\frac{dR_{\text{sex}}}{dt} = s \cdot (1 - R_{\text{sex}}) - c \cdot R_{\text{sex}} \cdot N_{\text{resource}} \tag{5}$$

In this Formula,Rsex represents the gender ratio of lampreys(the number of male lampreys divided by the total lamprey population),sis the gender ratio growth index,and c is the impact indexof environmental resources on the gender ratio. As indicated in the problem statement, when resources are scarce in the environment, the proportion of males increases, so we subtract h ·Npredator ·Nlamprey to simulate the impact of environmental resource quantity on the gender ratio of lampreys.

After programming, we obtained the solution to the system of differential equations,as shown in Figure 4.

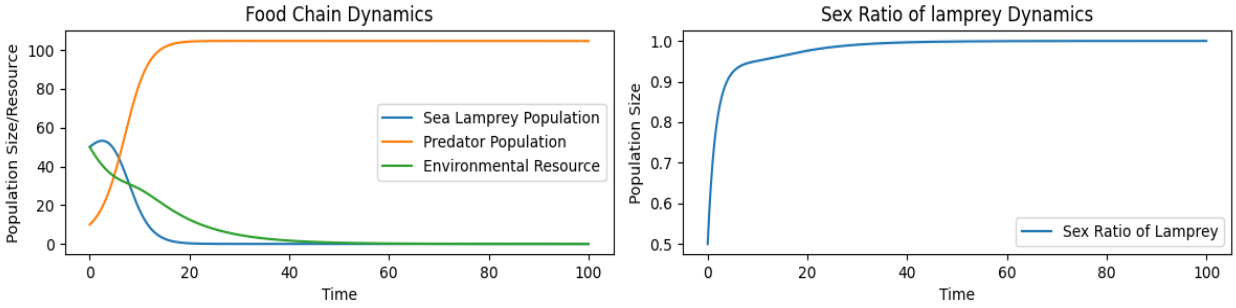


Figure 4: The Impact of Gender Ratio on the Food Web

From the graph, we can observe that over time, the gender ratio of lampreys gradually increases, and the population of predators also rises. Meanwhile, the quantity of environmental resources decreases, and after reaching itspeak, the population of lampreys starts to decline.

Therefore, we can conclude that the gender ratio of lampreys is generally positively correlated with the population of predators. The gender ratio of lampreys is typically negatively correlated with the quantity of environmental resources. Meanwhile, the population of lampreys reaches its maximum value when the gender ratio reaches a certain threshold.

This result also explains the condition posed in the question: why is the gender ratio of lampreys higher in situations of food scarcity? This is because lampreys, in response to the scarcity of food resources, adjust their gender ratio by increasing it, thereby causing a reduction in their own population to adapt to the limited food environment.

4.1.2 Ecological Habitat Model

The gender ratio has profound effects on habitat utilization within ecosystems, serving as a significant factor influencing biodiversity and community stability. To investigate the impact of gender ratios on habitat utilization within ecosystems, we have developed a habitat utilization rate model,as shown in Formula 6.Through this study, we aim to enhance our understanding of the role of gender ratios in ecosystems, thereby refining a comprehensive ecosystem model.

$$R_{\text{occupation}} = C_{\text{habitat}} \cdot (1 - R_{\text{sex}}) \cdot R_{\text{resource}} \tag{6}$$

In the formula,$R_{occupation}$ represents the habitat occupancy rate,$C_{habitat}$ denotes habitat capacity,R_{sex} signifies the proportion of male lampreys, and $R_{resource}$ denotes the environmental resource utilization rate.

Due to the inclination of lampreys to spawn in specific regions, during the breeding season, there is a higher occupancy rate of habitat. Consequently, we incorporate the proportion of female lampreys$(1 - R_{sex})$ as a contributing factor. Simultaneously, higher resource utilization rates in a region lead to increased population aggregation, resulting in a higher habitat occupancy rate. Therefore, we consider the resource utilization rate as an influencing factor.

We will iterate the model. Assuming 100 iterations, with an initial male proportion: $R_{sex}=0.56$, an initial resource utilization rate: $R_{resource}=0.67$, and an initial habitat capacity: $C_{habitat}=1.2$.

Each iteration process consists of two steps:

1.Increase the degree of randomness to introduce more variability into the results:

- Increase the male proportion by α, $\alpha \in [-1, 1]$
- Increase the resource utilization rate by β, $\beta \in [-1, 1]$

2.Ensure that the data remains within a reasonable range.:

- Limit $R_{sex} \in [-1, 1]$
- Limit $R_{resource} \in [-1, 1]$

After programming, the results of the iterative model are shown in the Figure 5.

From the graph, we can observe that the curve trends of the gender ratio of lampreys and the habitat occupancy rate are roughly consistent. Therefore, we speculate that the two are positively correlated.

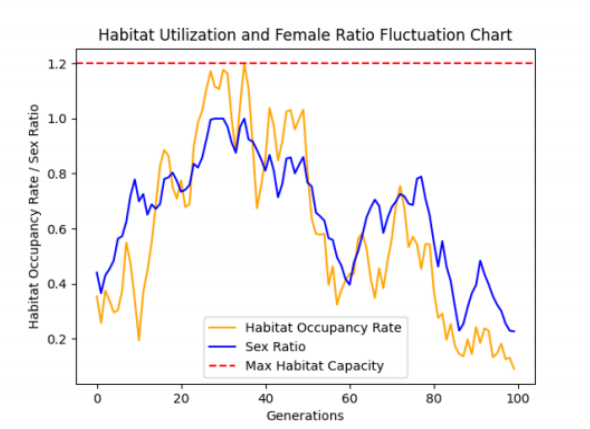


Figure 5: Habitat Occupancy Rate vs. Gender Ratio Relationship Chart

4.2. Advantages and Disadvantages

4.2.1 Evolutionary Game Model

Due to the findings from the previous research, we now understand that lampreys can adapt to environmental changes by altering their gender ratio. Therefore, we consider the ability to change gender ratio itself as an advantage for lampreys. In the following, we have simulated the process of changing the gender ratio in lampreys.

We have developed an Evolutionary Game Model[4] based on the Moran process to simulate the competitive game between female and male lampreys in natural conditions. In this model, individual lampreys can choose to cooperate (Strategy 0: jointly and rationally utilize limited resources, increasing the number of both female and male individuals simultaneously) or betray (Strategy 1: competing for resources, decreasing the number of both female and male individuals simultaneously). The payoff of individuals is determined by a payoff matrix, reflecting the characteristics of the Prisoner's Dilemma where the betrayer's payoff is higher than that of the cooperator.

The payoff matrix for the evolution game model based on the Moran process is structured as follows in the context of the Prisoner's Dilemma:

Table 2: matrix for the evolution

	Cooperate(Strategy 0)	Betray(Strategy 1)
Cooperate(Strategy 0)	R	S
Betray(Strategy 1)	T	P

- R(Reward) represents the payoff when both individuals cooperate,
- S(Sucker's payoff) represents the loss when a cooperator encounters a betrayer,
- T(Temptation) represents the payoff when a betrayer encounters a cooperator,
- T(Punishment) represents the payoff when both individuals betray.

Typically, in a Prisoner's Dilemma scenario, $T>R>P>S$, indicating that the betrayer receives the highest payoff, while the cooperator's payoff is relatively lower.

In each round of the game, two individuals are randomly selected to participate. The payoff for each individual is contingent on both their strategy and that of their opponent. Subsequently, individuals update their strategies through the Moran process: if one individual's payoff is lower than the other's, there is a certain probability that it will adopt the strategy of the other player.

This probability is determined by the Fermi function, as illustrated in Formula 7, which is dependent on the payoff difference between the two players.

$$P = \frac{1}{1 + e^{-(\Delta R/T)}} \tag{7}$$

- P represents the probability of adopting the opponent's strategy.
- ΔR represents the payoff difference between two players.
- T is a parameter controlling the probability distribution, commonly referred to as temperature. Higher temperature values lead to more evenly distributed strategy choices, while lower temperatures result in more extreme selections.

After multiple rounds of the game, we calculate the gender ratio of lampreys and plot the variation in the total number of lamprey individuals with the number of game rounds following each iteration,as shown in Figure 6.

4.2.2 Reproductive Success Rate Model

The reproductive success rate serves as a crucial metric for assessing the advantages and disadvantages of a population. Below, we investigate the impact of lamprey gender ratio on its reproductive rate and established a reproductive success rate model,as shown in Formula 8.

$$S_{\text{reproduction}} = f\left(R_{\text{sex}}, N_{\text{resource}}\right) \tag{8}$$

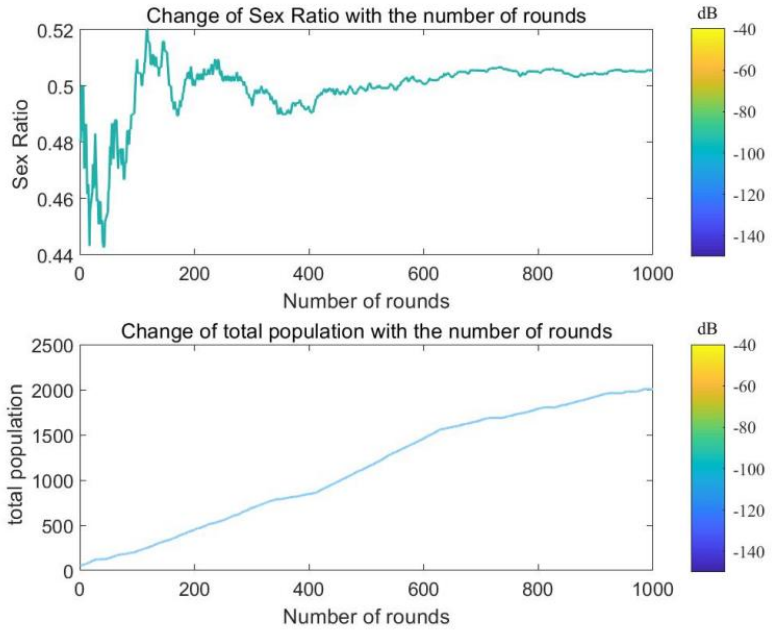


Figure 6: Evolution Game Model

$$f\left(R_{\text{sex}}, N_{\text{resource}}\right) = \varepsilon \cdot R_{\text{sex}} \cdot \left(1 - R_{\text{sex}}\right) \cdot N_{\text{resource}}$$

In the formula, $S_{\text{reproduction}}$ represents the reproductive success rate, R_{sex} represents the gender ratio, and N_{resource} represents the environmental resource quantity.ε is the reproductive success coefficient.

Here, we assume that the environmental resource quantity is constant and does not mutually influence the gender ratio. We set up the equation in this way because the closer the gender ratio is to a balanced state and the richer the environmental resources, the higher the reproductive success rate.

After programming, we obtained a graph illustrating the relationship between gender ratio and reproductive success rate,as shown in Figure 7

From the image, we can observe that when the gender ratio is balanced, the reproductive success rate is the highest, indicating an advantage for the lamprey population. Conversely, as the gender ratio approaches 0 or 1, the reproductive success rate decreases, signifying a disadvantage for the lamprey population.

4.2.3 The Resource Utilization Efficiency Model

As widely recognized, resource utilization efficiency is a crucial metric for assessing the survival status of a population. By establishing the relationship between resource utilization efficiency and gender ratio, we aim to explore the advantages and disadvantages arising from changes in gender ratio. To achieve this, we have developed a resource utilization efficiency model,as shown in Formula 9.

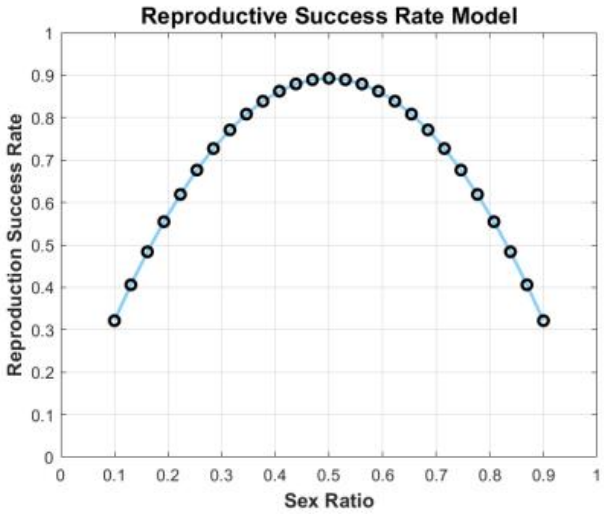


Figure 7: Production Success Rate

$$R_{\text{resource}} = f\left(R_{\text{sex}}\right)$$
$$f\left(R_{sex}\right) = \lambda \cdot \frac{R_{sex}}{1 - R_{sex}} \tag{9}$$

In the formula, R_{resource} represents resource utilization efficiency, and λ is the efficiency coefficient. Based on the findings from the first question, as the gender ratio increases, the lamprey's adaptability to adverse environments strengthens. Therefore, we assume a positive correlation between resource utilization efficiency and gender ratio.

After programming, we obtained the graph of the resource utilization efficiency model, as shown in Figure 8.

Analyzing the graph, we can deduce that when the gender ratio is low, the resource utilization efficiency is also low, indicating a disadvantage for the lamprey population. Conversely, when the gender ratio is high, the resource utilization efficiency is high, signifying an advantage for the lamprey population.

4.3. The Impact of Gender Ratio on Ecosystem Stability

4.3.1 Ecological System Dynamics Evolution Model

Based on the research in the first question, we have already learned about the impact of changes in lamprey gender ratio on the predator population. To analyze the influence of gender ratio on the overall stability of the ecosystem, we have to increase the complexity of the model,

incorporating more components into the food chain to ensure the accuracy and effectiveness of our model.

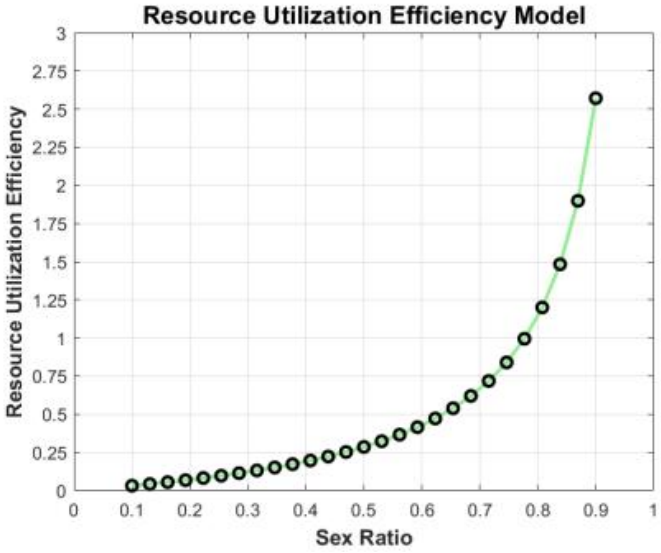


Figure 8: Resource Utilization Efficiency

In the ecosystem, there are generally three types of organisms that coexist with lampreys. The first type of organism competes with lampreys, the second type coexists independently without affecting lampreys, and the third type coexists as a parasite with lampreys. We will introduce these three types of organisms into the ecosystem and discuss the impact of lamprey gender ratio on them.

Here, we will still use the Logistic model to model the three types of organisms with lampreys. In a limited environment and resources, the logistic equation for population growth is:

$$\frac{dN}{dt} = r \cdot N \left(1 - \frac{N}{K}\right) \tag{10}$$

r is the natural growth rate of the population,r > 0. N is the population size of the species. $\frac{N}{K}$ represents the population growth of the species. $1 - \frac{N}{K}$ represents the carrying capacity, which is the maximum population size that the environment can sustain with limited resources.[5]

Now, with the introduction of interactions between populations, we can obtain the following Formula 11:

$$\frac{dX_i}{dt} = r \cdot X_i \left(1 - \frac{X_i}{k_i} + \sum_{j=1}^{j} a_{ij} \cdot \frac{X_j}{k_j}\right) \tag{11}$$

Let the population sizes be denoted as X_i, where i =1, 2, 3, … Now, let's discuss the interactions between each pair of populations.

Where X_i and X_j both represent the population sizes of biological species in the ecosystem. The relationship between X_i and X_j is cleverly embedded in the values of a_{ij} and a_{ji}, as shown in the following table.

Table 3: Nine types of competitive and cooperative relationships among populations.

	$a_{ji} > 0$	$a_{ji} = 0$	$a_{ji} < 0$
$a_{ij} > 0$	Mutual promotion	j promote i	i preys on j
$a_{ij} = 0$	ipromote j	No mutual influence	iinhibits j
$a_{ij} < 0$	j preys on i	jinhibits i	Mutual inhibition

In order to find the equilibrium point of the system, we can set $\frac{dx_i}{dt} = 0$.

Here, we only consider the pairwise interactions between lamprey and another organism. We simulated the competitive mode, independent coexistence mode, and parasitic coexistence mode. The simulation results are shown in the Figure 9.

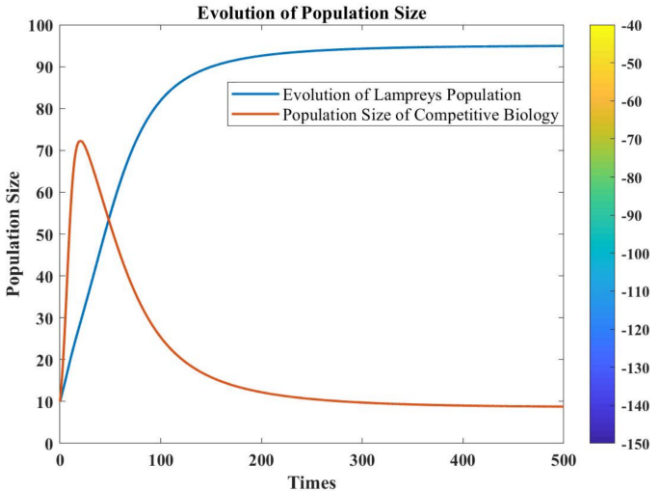


Figure 9 (a): Competitive Mode

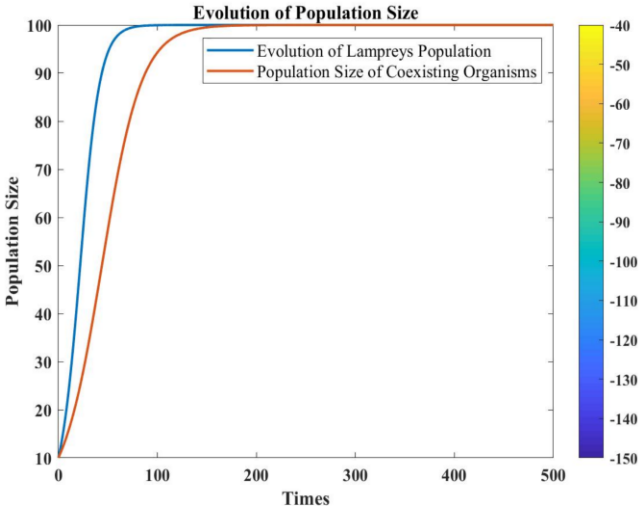


Figure 9 (b): Independent Coexistence Mode

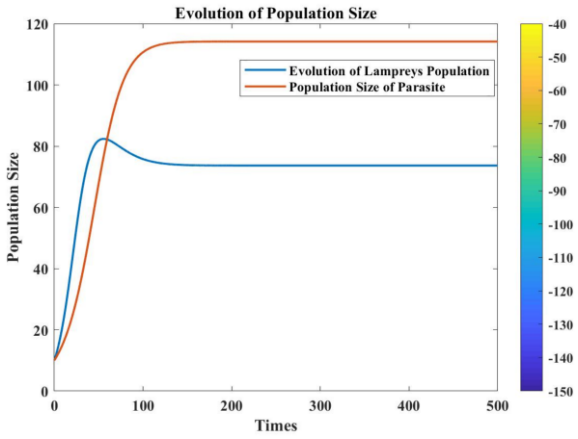


Figure 9 (c): Parasitic Coexistence Mode

4.3.2 Ecological System Stability Composite Index Model

In order to comprehensively assess the stability of the ecological system, we have established an Ecological System Stability Composite Index Model. The model incorporates indicators such as biodiversity, spatial utilization efficiency, and population reproduction rate. Below, we will model these indicators:

• Biodiversity (A_1): In a mature and intact ecological system, assuming that there are constant random extinctions or evolutions of organisms, we set A to randomly oscillate around 0.5 to simulate the evolutionary or extinction events in the ecosystem due to unforeseen natural events.

• Spatial Utilization (A_2): The second indicator is defined as the total biomass in the system divided by the total space (environmental capacity) available in the system.

$$A_2 = \frac{\sum_{i=4}^{4} X}{\sum_{i=4}^{4} K_i}$$

• Population Reproduction Rate (A_3): Using the Euler method to solve the differential equations in MATLAB, we obtain arrays representing the changes in population quantities over time. We divide time into small intervals, calculate the average population quantity within each interval, and then compute the one-dimensional distance between this average value and the initial population quantity. Repeating these steps for each time interval, we derive distance values for each population, representing the stability of their growth. These values are then incorporated into the comprehensive indicator of ecosystem stability.

After normalizing the aforementioned indicator data and determining the weights using the entropy weight method, we obtain the following comprehensive indicator Formula:

$$ST = 0.51 \cdot A_1 - 0.32 \cdot A_2 + 0.75 \cdot A_3$$

By setting three sets of gender ratio values, namely 0.36, 0.60, and 0.78, we obtained the visual results of the comprehensive indicator function under different gender ratios,as shown in Figure 10.

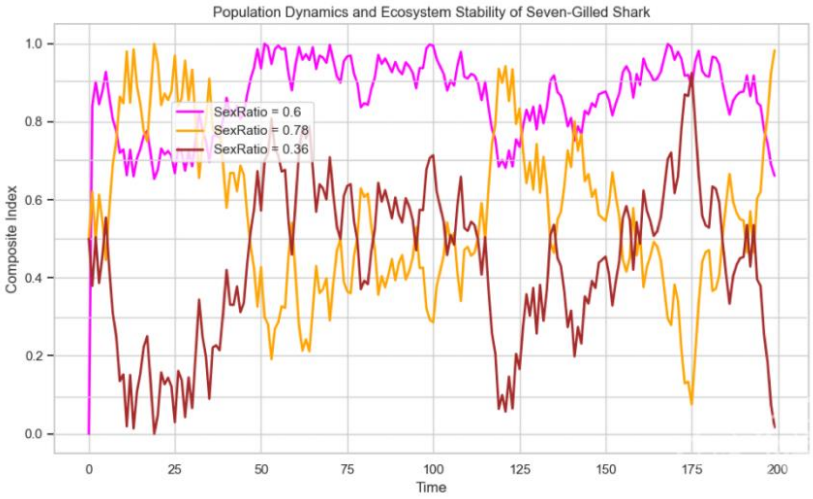


Figure 10: Population Dynamics and Ecosystem Stability of Seven-Gilled Shark

From the above figure, we can observe that when the gender ratio equals 0.6, the fluctuation amplitude of the composite indicator curve for ecosystem stability is the smallest.

Conversely, when the gender ratio is 0.36, the fluctuation amplitude of the composite indicator curve is the largest. This further confirms the findings in section 4.3.1: the closer the lamprey gender ratio is to 0.64, the better the stability of the ecosystem.

4.4. The impact of variable gender ratios on parasites.

4.4.1 Parasitic Game Model

Firstly, we created a comprehensive set of edges for the food web. We established the predator-prey relationships, including both male and female lampreys, and their food sources such as larger fish, smaller fish, crustaceans, etc.The ecosystem network composed of all organisms is shown in Figure 11.

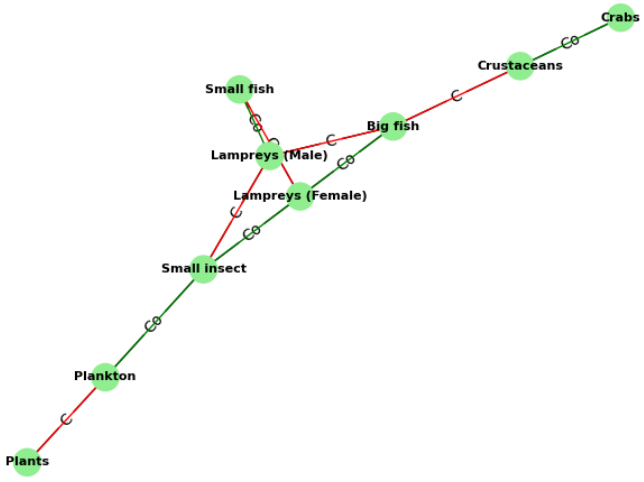


Figure 11: The Ecosystem Network

Later, we applied evolutionary game theory and introduced a model with parasitic organisms that inhibit the growth of lampreys. In this model, we achieved this by reducing the penalty for parasites choosing betrayal and increasing the probability of parasites choosing betrayal, simulating the competition between parasites and lampreys.Finally, we obtained the curve depicting the relationship between gender ratio and parasite quantity,as shown in Figure 12.

From the graph, we can observe that when the gender ratio is around 0.6, the total number of parasites is low. When the gender ratio is around 0.5, the total number of parasites is relatively

high. Based on the research in previous questions, we know that when the gender ratio is close to 0.64, the total population of lampreys reaches its maximum, and at this point,there is intense competition with parasites, leading to a lower parasite count.

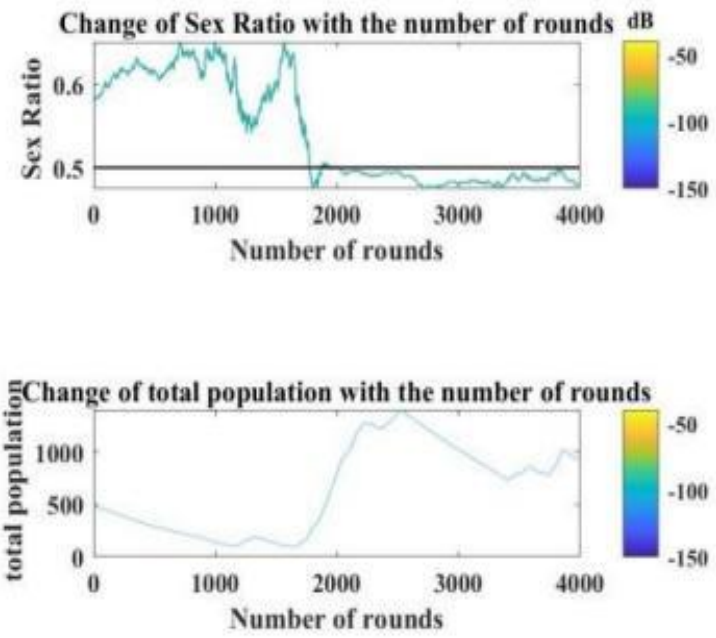


Figure 12: Parasitic Effect Curve

At the same time, we consulted data from Lake Michigan in the United States, as shown in Figure 13. TFM is an indicator of a chemical substance used to measure the eradication of parasites, and it is positively correlated with the parasite count. From the graph, we can observe a negative correlation between the lamprey population and the parasite count. Therefore, we can conclude that as the gender ratio deviates further from 0.64, the lamprey population decreases, providing an advantage to the parasite population.

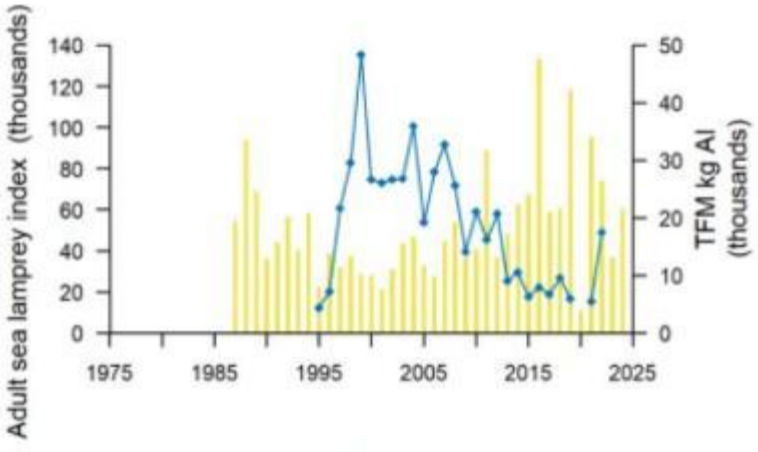


Figure 13: Lake Michigan data

5. Sensitivity Analysis

We conducted a sensitivity analysis on the parameters of the fundamental Logistic population growth model.

We observed the variation in the population size of lampreys under different growth rates, as depicted in Figure 14.

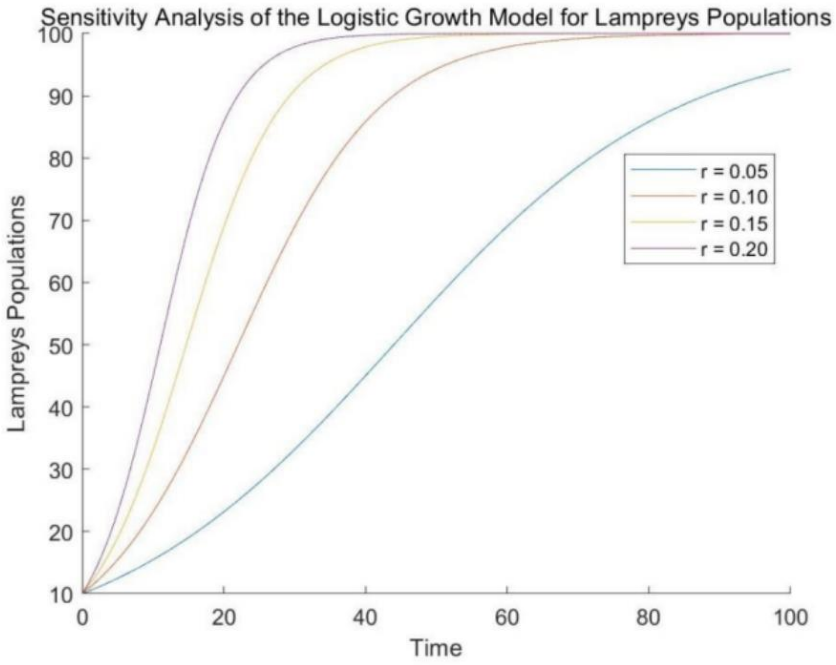


Figure 14: Analysis 1

It can be observed that the population size undergoes significant changes under different growth rates.

Subsequently, we introduced a competing species and constructed a relatively simple population interaction model dependent on growth rates and competition coefficients. We then conducted sensitivity analysis, as illustrated in Figure 15.

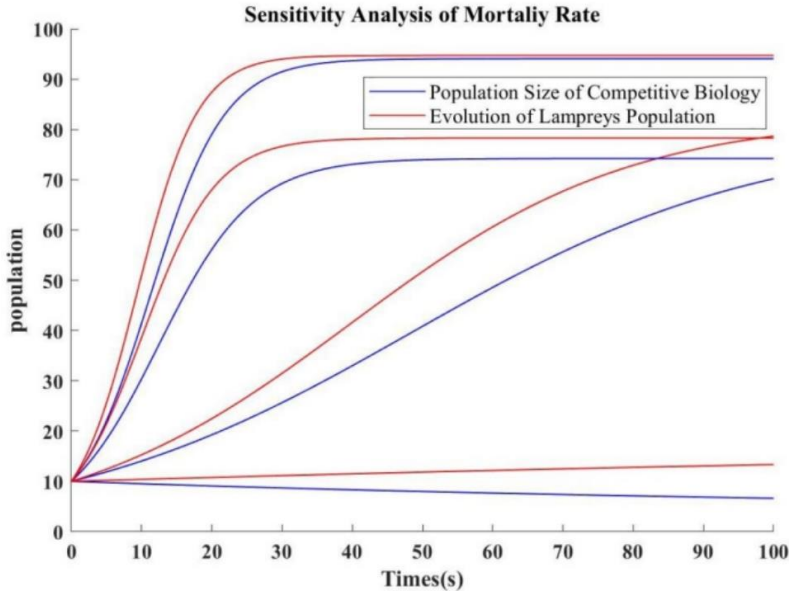


Figure 15: Analysis2

We found that the model still heavily relies on parameter variations

In the ecological system dynamic model we constructed, we incorporated the gender ratio of lampreys as a parameter influencing the model variations,as shown in Figure 16.

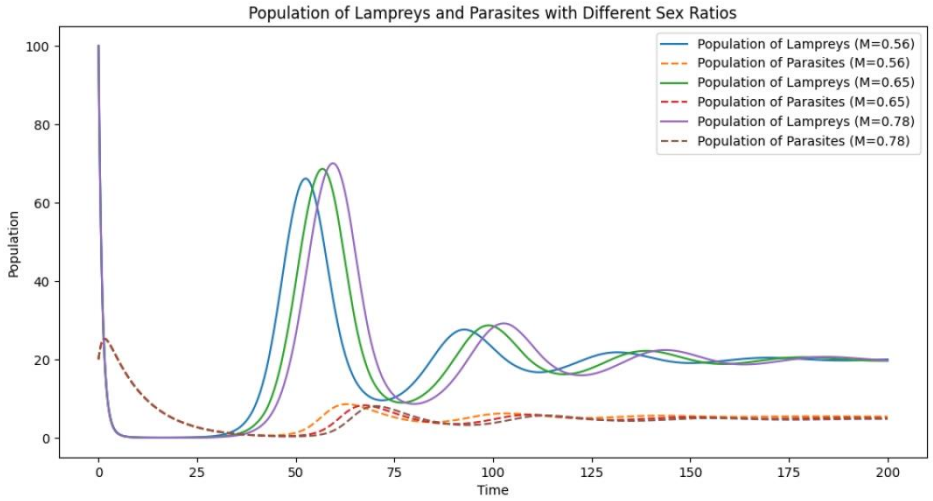


Figure 16: Analysis3

It can be observed that the model exhibits apparent robustness, as the population sizes of lampreys and parasites show minimal fluctuations under different gender ratio settings.

6. Model Evaluation

6.1. Strengths

• Comprehensive Summary: Our model takes into account various impacts of lamprey gender ratio on the ecosystem, including food chains, habitats, reproduction, resource utilization, stability, and more. It illustrates the complexity and diversity of gender ratio changes in lampreys.

• Innovation: Our model, grounded in game theory and dynamical systems theory, innovatively defines payoff matrices, reproductive success rate functions, resource utilization rate functions, comprehensive evaluation indices, and more. This provides new interpretations and evaluation methods for lamprey gender ratio changes.

• Practicality: Through numerical simulations and sensitivity analysis, our model has yielded practical conclusions, such as the ecosystem being most stable when the gender ratio approaches 0.64 and the advantageous conditions for parasites when deviating from this ratio. This provides valuable insights for the conservation and management of lampreys.

6.2. Weaknesses

• Parameterization: Our model involves numerous parameters, such as payoff matrices, reproductive success rate functions, resource utilization rate functions, comprehensive evaluation indices, etc. The values of these parameters may be influenced by data sources, method selection, subjective judgment, etc., introducing a degree of uncertainty and bias.

• Simplification: For analytical convenience, our model has made some simplifying assumptions, such as neglecting factors like age structure in lampreys, genetic variations, environmental disturbances, etc. These simplifications may impact the applicability and precision of the model.

7. Conclusion

In this comprehensive study, we have delved into the intricate relationship between the gender ratio of lampreys and the broader ecosystem they inhabit. Using a variety of mathematical models, including Logistic models, Game Evolution Models, and Ecological

System Dynamics Evolution Models, we have explored the implications of these gender ratio changes on predator-prey interactions, resource utilization, habitat occupancy, and ecosystem stability. While our models offer valuable insights, it is important to acknowledge their limitations. The parameterization of our models, while based on available data and theory, still involves a degree of uncertainty. Additionally, our models have made simplifying assumptions to facilitate analysis, potentially limiting their real-world applicability. Overall, our study provides a comprehensive understanding of the impact of lamprey gender ratio on the ecosystem, offering valuable insights for the conservation and management of these unique fish species. Future research could further explore the impact of other factors, such as age structure, genetic variations, and environmental disturbances, on lamprey gender ratio and ecosystem stability.

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