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A Dual Role Study of Lampreys in Ecosystems Based on Multi-Model Analysis

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Abstract. With environmental changes and increased human activities, changes in the sex ratio of Lampreys, a key secondary consumer, have a significant impact on the health and stability of aquatic ecosystems. To address this, this study created a seven-gill eel population prediction model based on the Lotka-Volterra Model incorporating a Bayesian Hierarchical Model suitable for changes in the seven-gill eel population. The model predicted the population density of Lampreys based on the sex ratio of Lampreys, analyzed the stability of the ecosystem based on the food web of Lampreys and concluded that the ecosystem was unstable when the sex ratio of Lampreys was close to 1:1, and the ecosystem became stable when the sex ratio of Lampreys was far away from 1:1. At the same time, this study also determined that Lampreys have the advantages of high survival rate, high life span, and high resource utilization in the ecosystem through the Topsis principle. The study of Lampreys populations is essential for understanding and protecting aquatic ecosystems, as well as helping to monitor water quality and environmental change. Thus, the study of their population size, distribution, and behavior contributes to the understanding and protection of aquatic ecosystems.

Keywords: Sex ratio; Ecosystem stability; Predictive modeling of Lampreys populations; Topsis modeling principles.

1. Introduction

In recent years, with the changes in the ecological environment and the increase in human activities, the balance of the ecosystem is facing unprecedented challenges [1]. Lampreys, as a key secondary consumer in the food web, its survival directly affects the health and stability of the whole aquatic ecosystem [2]. The sex ratio of Lampreys, as one of its biological characteristics, has an important impact on its population dynamics and interactions with other species.

This study combined the Lotka-Volterra Model and the Bayesian Hierarchical Model to study this field. The Lotka-Volterra Model is widely used in the fields of predicting predation among species in ecosystems, corporate competition, and neural network competition [3]. The Bayesian Hierarchical Model was proposed by Bayesian and has been widely used in the field of predicting the sex ratio of species populations.

The primary source of data for this study was a field study that demonstrated that sex determination in sea lampreys is directly influenced by juvenile growth rate [4]. Our team conducted a study on the changes in population density in Lampreys based on the data provided in the above paper. The focus of this study was on predicting the population density of lampreys, so in this study the Lotka-Volterra Model was used as the basis for a Bayesian hierarchical model combined with the Gompertz Model to create the predictive modeling of Lampreys populations, which predicts the population size of lampreys based on physiological characteristics specific to lampreys in the ecosystem. Meanwhile, the principle of comparing the optimal solution of the Topsis model was used in the study to select four unique characteristics of the lamprey population and compare them with other species to summarise the strengths and weaknesses of the lamprey in the ecosystem.

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2. Impact of Lamprey Sex Ratio Changes on Ecosystem Stability

2.1. Bayesian Hierarchical Model-Based Prediction of Sex Ratio

The Bayesian Hierarchical Model was applied to predict the sex ratio of adult sea cormorants in different stream and lake areas [4]. In this model, whether an adult tagged sea cormorant captured from these areas each year is a male or not is treated as a Bernoulli random variable [4], and its probability of being a male is defined accordingly:

$$logit\left(p_{i,y}^{type}\right)=\alpha_i^{type}+\beta_i^{type}*y \tag{1}$$

Here, "i" represents a specific stream or lake area, "y" represents the number of years to reach maturity after release, and "type" distinguishes whether the site is a river or a lake. Each site-specific parameter is determined by a combination of the population mean for that type of site and its deviation from that mean.

$$\alpha_i^{type}=\alpha_0^{type}+\delta_i \tag{2}$$

$$\beta_i^{type}=\beta_0^{type}+\gamma_i \tag{3}$$

This model considers the effect of the sex ratio on the population of Lampreys. The change in the sex ratio receives the influence of environmental factors, and the change in sex ratio under different conditions is modeled with relevant data.

2.2. Predation competition model for Lotka-Volterra population based on the Gomperz

In this section, it is considered that the sex ratio of lampreys is influenced by external environmental factors that may lead to changes in population size. Therefore, a combination of Bayesian hierarchical model and Gompertz's species prediction model was used in the study, along with the introduction of ambient temperature factor to predict sex ratio and species population density based on known data.

For fish populations, the Gompertz growth law is more appropriate than the Logistic growth law [5]. Under ideal survival conditions, fish populations will initially increase rapidly, but the rate of growth will gradually slow down as resources and environmental constraints are imposed. As the population continues to grow, it gradually reaches the carrying limit of the environment, showing a growth pattern: rapid growth at the beginning and a significant slowdown as it approaches the limit of environmental capacity. After reaching a certain inflection point, population growth goes through a long period of linear growth. When the population is large, the survival pressure on newborn individuals increases due to the presence of predators or competition for resources within the population, which limits the infinite expansion of the population size. In the absence of migration, population growth to near the limit of environmental capacity can be rapid, but the inhibiting effects of factors such as population migration and predation can slow this growth. This phenomenon is a distinctive feature of fish population growth, so the population growth will become slow as it approaches its limit, and the shape of the Gompertz growth curve reflects this characteristic well [3]. Thus, the study chose to use the Gompertz model to construct a more appropriate model for the problem. Example comparison figure 1 is as follows:

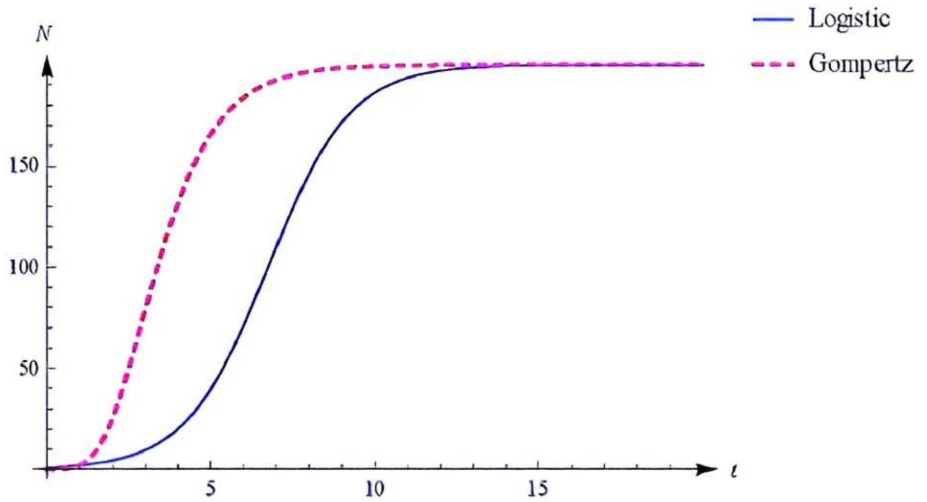

Figure 1. Curve Comparison Chart

To predict future population densities of different species, the study was designed to construct a differential equation based on the Gompertz model. The Gompertz model is a commonly used mathematical method for describing changes in the number of organisms and is also a biological growth model. However, it is necessary to modify the Gompertz model at the same time considering the variation in the sex ratio of lampreys, so it was decided to opt for combining the Gompertz model with a Bayesian hierarchical model. In this case, the Bayesian hierarchical model was used to predict the sex ratio of the lanternfish population [6].

In this section, the study will consider the impact that an increase in the lanternfish population may have on other species in the same ecosystem. According to the model, it can be concluded in the study that sex ratio has a positive effect on population size, but since the effect of changes in the sex ratio of lampreys on the ecosystem is a multilevel and multifaceted problem, it is assumed that only changes in population dynamics, such as competition and predation, between different species need to be considered to simplify the model. Sex ratio was used as a parameter of the model in the study so that the model could be varied with time and environment.

Species competition is one of the most important ecological processes affecting the evolution of ecosystems, and the Lotka-Volterra Model is a classic and well-known model for describing the competitive relationships between multiple species, and it can also be used to describe the relationship between two species [7]. Here, the study needs to consider the effect of changes in the sex ratio of Lampreys on the intensity of predation and competition between Lamprey populations and other species, so the model was slightly modified in this study to cope with this situation. The model equations are as follows:

$$d\frac{N_A}{dt} = r_A * N_A * \left(1 - \frac{N_A}{K_A}\right) - c_{AB} * N_A * N_B - c_{AC} * N_A * N_C \tag{4}$$

$$d\frac{N_B}{dt} = r_B * N_B * \ln\frac{K_B}{N_B} - c_{BA} * N_B * N_A - c_{BC} * N_B * N_C \tag{5}$$

$$d\frac{N_C}{dt} = r_C * N_C * \ln\frac{K_C}{N_C} - c_{CA} * N_C * N_A - c_{CB} * N_C * N_B \tag{6}$$

Figure 2 shows that the sex ratio of Lampreys in riverine waters is gradually increasing and in marine waters is gradually converging to 1. The sex ratio of Lampreys in the riverine area for the next three years is 85% according to the results of data prediction [5] [6]; and the sex ratio in the marine area for the next three years is 53%.

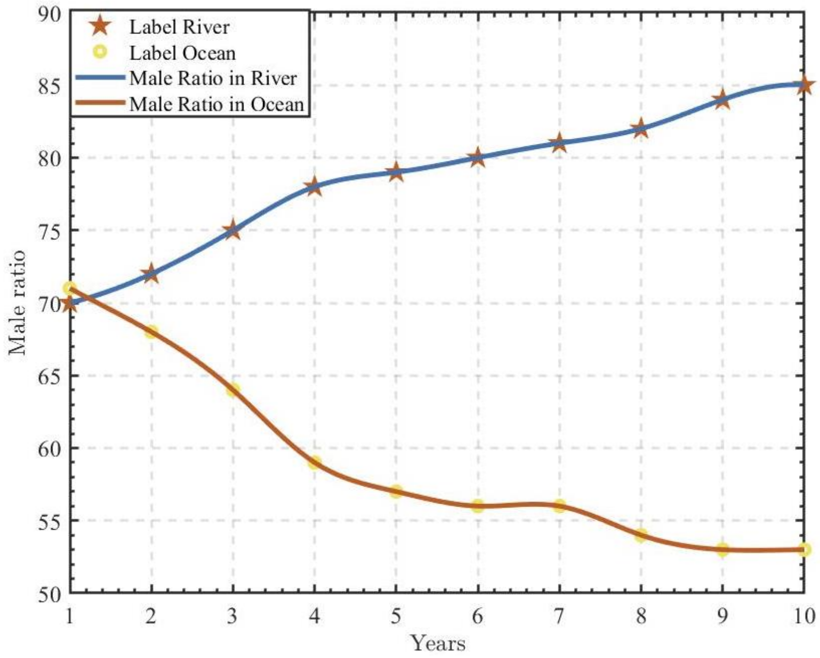

Figure 2. Graph of changes in sex ratio

In different waters, the sex ratio of Lampreys changed significantly, and it is the freshwater waters that have significantly fewer resources than the marine waters, and the ecosystem resources of the two environments are significantly different, which affects the sex ratio of the Lampreys to change accordingly

Due to the physiological nature of the Lampreys, both male and female Lampreys die naturally after fertilization and spawning. Therefore, the sex ratio of Lampreys species in turn affects the birth rate of the species [8].

From figure 3, the birth rate of the Lampreys population reached a maximum at the population sex ratio of 1:1, and then a significant drop-in birth rate occurred as the sex ratio gradually increased.

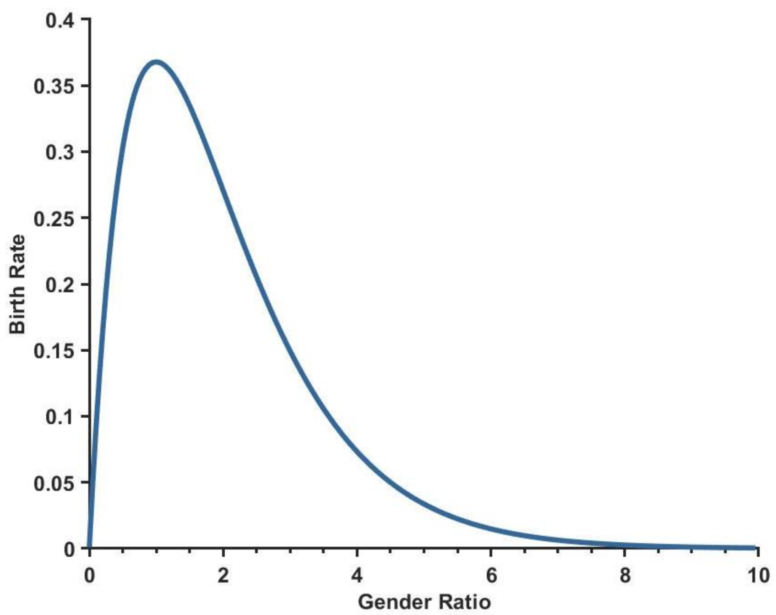

Figure 3. Birth rate curve for the Lampreys population

Considering the computational efficiency of the model and model realism, the study created an idealized three-species eco-system, which contains a secondary consumer, a primary consumer, and a producer [9]. Lampreys is in the role of secondary consumer in this ecosystem. The three species are very different in species birth rate, death rate, and population maximum holding capacity to simulate the competition among species in the real environment

In this model, water temperatures are assumed to be uniform and optimal for the biological activity of all three species that have reproduced; in short, the ecosystem's predatory competition relationship is the only factor the study consider [10]. The initial densities of the populations were 80 for species A, 20 for species B, and 5 for species C. The results of the model are shown in figure 4:

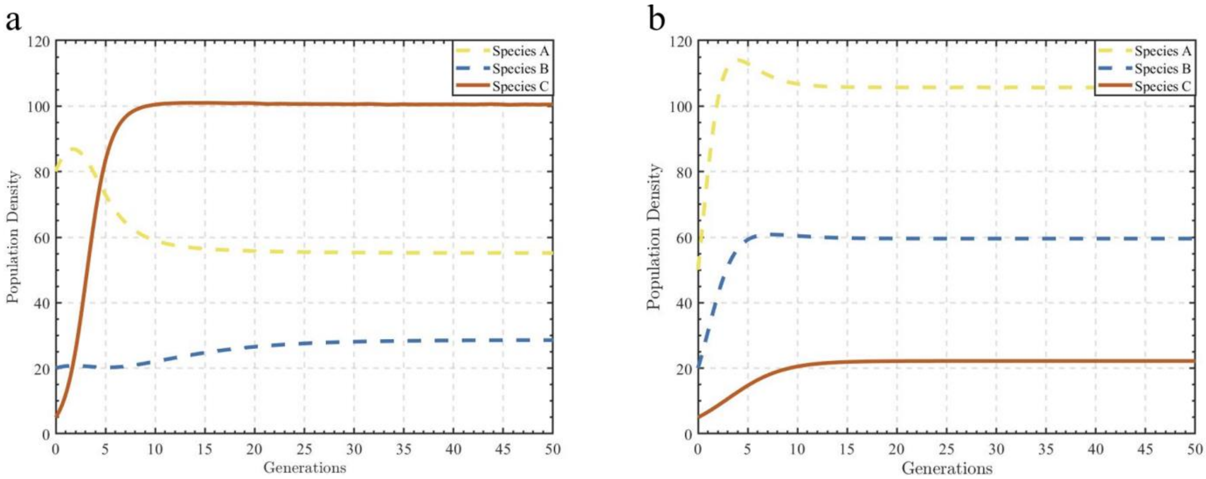

Figure 4. Curve of change in population density at a sex ratio Figure

a: sex ratio of 1:1. **b**: sex ratio of 4:1

By analysing the trends in the above curves, the study can draw the following important conclusions:

While species C, secondary consumers, had a low population density at the beginning, with the increment of the number of times the population reproduced, their density increased rapidly and gradually surpassed the other two species, forming a high competitiveness in the setup model. While the species of species A-producer and species B-primary consumer have higher initial density, with the increment of the number of times the population reproduces, their densities gradually decrease and then stabilize.While the species of species A-producer and species B-primary consumer have higher initial density, with the increment of the number of times the population reproduces, their densities gradually decrease and then stabilize.

The population density of species A declined significantly, but in a normal ecosystem, the population density of species A should be the largest among the three species. At the same time, the sum of the population densities of the three species is gradually increasing. The change in the sex ratio of Lampreys populations led to a significant change in the number of organisms in the normal food chain of the ecosystem, making the food web of the ecosystem vulnerable to systemic collapse, and at the same time, the sum of the population densities of the species increased, so the change in the sex ratio of the Lampreys is threatening to the living space of the population in the ecosystem.

2.3. Sex Ratios and Parasite Population Levels in Lampreys

Interspecific interactions between lampreys and parasites were also modelled during the study based on the Lotka-volterra model and the Gompertz model, and the advantage gained by parasites was answered by comparing the changes in the density of parasite populations over time for different lamprey sex ratios [11].

$$d\frac{N_{\mathrm{H}}}{dt} = r_{\mathrm{H}} * N_{\mathrm{H}} * \ln\frac{K_H}{N_H} - a * N_{\mathrm{h}} * N_{\mathrm{p}} - b * N_{\mathrm{h}} * N_{\mathrm{p}} \tag{7}$$

$$d\frac{N_{\mathrm{p}}}{dt} = r_{\mathrm{p}} * N_{\mathrm{p}} * \left(1 - \frac{N_{\mathrm{p}}}{K_{\mathrm{p}}}\right) - c * N_{\mathrm{p}} * N_{\mathrm{H}} - d * N_{\mathrm{p}} * N_{\mathrm{H}} \tag{8}$$

Comparative analysis of the curves of parasite population density over time in Lampreys with sex ratios of 1:1 and 4:1, the following phenomena can be observed: when the sex ratio was high (4:1), the parasite population was overall lower and the magnitude of the change was smaller; while when the sex ratio was balanced (1:1), the parasite population was overall higher and the magnitude of the change was larger. Ecosystems with variable sex ratios in Lampreys populations can influence parasite survival and accordingly provide survival advantages for parasites. When the sex ratio of Lampreys was high, the number of males was high, the population of Lampreys was low, and the parasites obtained less nutrition from the Lampreys population, which resulted in a decrease in the parasite population, whereas when the sex ratio of Lampreys was changed from a high to a balanced one, more parasitism opportunities and nutrient resources were available to increase the survival rate of the parasite population accordingly. In addition, changes in the sex ratio of host Lampreys will make the parasite population more adaptable to environmental changes and host immune responses, which can promote the genetic diversity and adaptability of the parasite to a certain extent. A comparison of the sex ratios of the relevant data populations is shown in Figure 5:

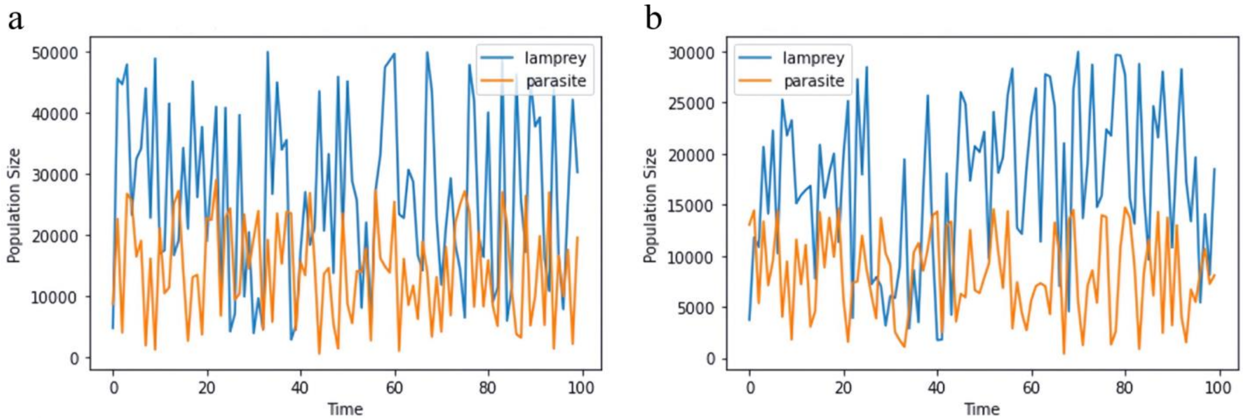

Figure 5. Comparison of populations at a sex ratio

a: sex ratio of 1:1. **b**: sex ratio of 4:1

3. TOPSIS Principle for Assessing Lampreys

3.1. The establishment of the simulation model

In this part, the study chose to analyze the three species ABC, where species A is the producers, species B is the primary consumers, and species C is the Lampreys. To address the relevant issues, this study modelled and analysed the strengths and weaknesses of lamprey populations using the principle of Topsis[12].

3.2. Analysis of experimental results

The topsis model is usually used for comprehensive analysis and evaluation of an object with multiple indicators, and the indicators affecting the evaluation results are regarded as multiple axes to construct a multi-dimensional space, and the optimal value and the worst value of each indicator are selected from all the objects to be evaluated, and the distances from the coordinate points of each object to be evaluated to the optimal value and the worst value are calculated by the following formula:

$$d_j^+ = \sqrt{\sum_{j=1}^{m} \left(y_i^+ - y_{ij} \right)^2}$$
$$d_j^- = \sqrt{\sum_{j=1}^{m} \left(y_i^- - y_{ij} \right)^2} \tag{9}$$

This study chose four characteristics of the three species: population fecundity, growth cycle, distribution range, and survival rate as the evaluation indexes of the Topsis model. The data provided by relevant literature were used to solve the model after data normalization.

3.3. Advantages and Challenges of Lamprey Populations

Figure 6 shows that species C is closer to the characteristic optimal solution in the vertical distance and far from the optimal solution in the horizontal distance.

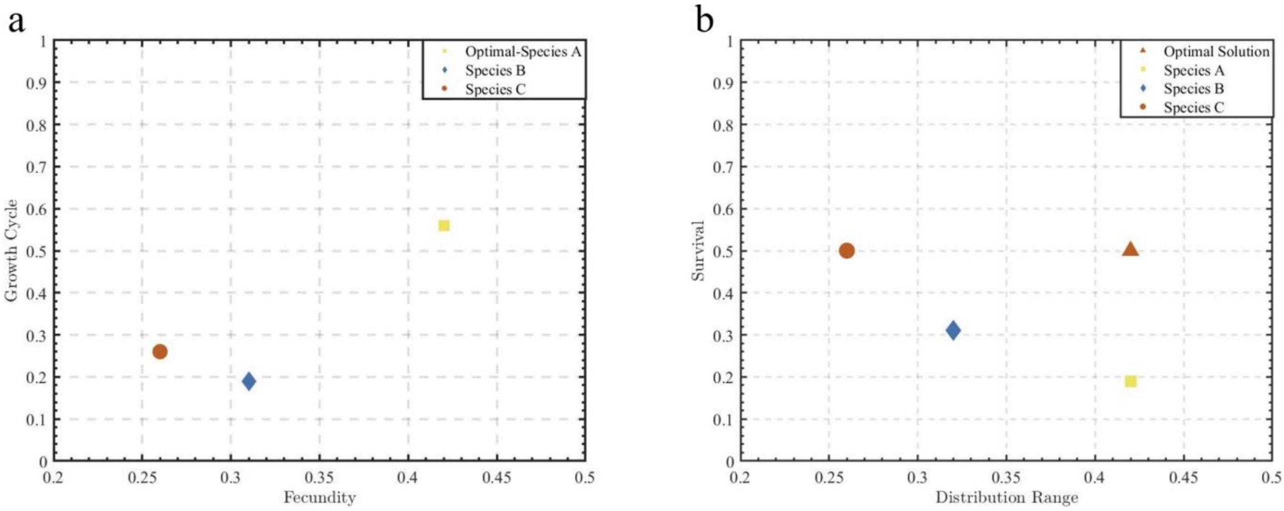

Figure 6. Feature Comparison Scatterplot

The results of the model runs and related literature lead to this conclusion:

The advantages of Lampreys are firstly the diet of Lampreys is very diverse and thus the survival rate of this species is higher compared to other species. They can eat small organisms such as zooplankton, insect larvae, crustaceans, and other small fish. This diversity of food sources allows Lampreys to better cope with food shortages or seasonal changes, thus ensuring a stable population.

Second, Lampreys have a metamorphic growth cycle, with larvae living in freshwater with undeveloped toothless eyes and feeding on microorganisms. After three or four times of metamorphosis, it takes 4 years before the adult migrates to the sea, and after 2 years of living in the sea, it migrates to the rivers to spawn to complete its life cycle.

Finally, the advantages of the Lampreys population are mainly reflected in the improvement of resource utilization efficiency. Adaptive adjustment of sex ratios allows Lamprey populations to adapt more efficiently to different environmental conditions, especially the availability of food resources. In environments where food availability is low, a higher proportion of males may help to reduce the overall demand for limited resources, as females typically require more resources to reproduce.

However, despite these obvious advantages, Lampreys still face several challenges and threats to their survival and reproduction.

The disadvantages are first, they are very sensitive to environmental changes, and teriorating water quality, drastic temperature changes, or the accumulation of pollutants can negatively affect Lampreys populations. Secondly, natural enemies and competitors of Lam- prey also pose a threat to their survival, and as a result, Lampreys have a relatively weak reproductive capacity.

In addition, human activities such as river development, water pollution, and overfishing may also pose a threat to the range of the Lampreys population.

Finally, excessive sex ratio adjustment may disrupt the ecological balance and affect the stability of the ecosystem. Changes in population sex ratios may produce unpredictable changes in ecological interactions with other species and may negatively affect, for example, predator-prey relationships.

4. Conclusion

Appropriate sex ratios of species are an integral part of ecosystems and maintaining ecosystem stability. The study will focus on the effects of the changing sex ratio characteristics of lampreys on the ecosystem and the interactions between lampreys and other species, thus modelling interspecific relationships in the ecosystem. Then, the Topsis modelling principle was used in the study to assign interspecific characteristics and to derive positive ideal solutions. Comparisons revealed that high survival, longevity and high resource utilization of lampreys in the ecosystem were advantages, while limited species range, susceptibility to environmental influences and disruption of ecosystem equilibrium were disadvantages.

This study reveals that the sex ratio of Lampreys is influenced by environmental resources, which can help solve the problem of the Lampreys population flooding and thus contribute to the stability of the ecosystem.

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