Quantitative Analysis of the Impact of Sex Ratio Bias on Ecosystems: The Case of the Sea Lamprey

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Abstract. In recent years, the widely distributed invasive parasitic species, sea lamprey, through its unique sex-influenced reproductive strategy, has had far-reaching impacts on host populations and aquatic ecosystems, highlighting the importance of species interactions in ecosystems and their importance to ecological balance. To address this, an EcoGenderDynamics model was developed to analyze the ecosystem effects of deviations in the sex ratio of sea lamprey populations. This study simulated the dynamic evolutionary pattern, as a result, the expression of the function of sex ratio and resource availability, and when the average resource availability was lower than 83% of the satiation level of each sea lamprey, the percentage of male lamprey increased significantly, gradually increasing from an initial 52% to 76.4%, and then slowly increasing and stabilizing. Also, a comprehensive assessment system was established to comprehensively evaluate the specific impact indicators of the sex ratio of the lamprey in the ecosystem. The results showed that in the case of insufficient resources, the population could improve its stability through the mechanism of adjusting the sex ratio, thus achieving a certain balance with the environment through a certain degree of showing weakness, indicating the importance of the ability to change the sex ratio for the survival of the population.

Keywords: Ecosystem Stability, Biodiversity, Interspecific Relationship, Dynamic Model.

1. Introduction

In recent years, the interactions between species in ecosystems and their impacts on ecological balance have become a hot topic in ecological research. Particularly, the effects of invasive species on native ecosystems have garnered widespread attention due to their potential to alter ecosystem functions and lead to biodiversity loss [1-2]. The sea lamprey, an invasive parasite species in the Great Lakes, has rapidly occupied a highly significant position in the food chain of the lakes since its introduction. It is noteworthy that the gender ratio of the sea lamprey can be influenced by environmental resources. When food supply is limited, the proportion of males in the population will significantly increase. This paper will investigate the impact of the sea lamprey's ability to alter its gender ratio based on resource availability on host and competitor populations, and even the entire aquatic ecosystem.

To establish a mathematical model describing ecosystems for quantitative analysis of various indicators, this paper embarked on using the Lotka-Volterra model proposed by American mathematician Alfred J. Lotka (1880-1949) and Italian mathematician Vito Volterra (1860-1940) and performed numerical solutions using finite differential methods. The Lotka-Volterra model is a landmark model in ecosystem research, which is used in the field of River Ecology [3-4], Global dynamics [5], Spreading dynamics [6-8], etc. Building upon this foundation, the system of differential equations has been expanded and refined to provide a more comprehensive description of the dynamic interactions within the system.

In this study, the EcoGenderDynamics Model (EGD), a statistical and ecological model based on the lamprey data from the Great Lakes Fisheries Commission (GLFC) and its control agencies, Fisheries and Oceans Canada (DFO) and the United States Fish and Wildlife Service (USFWS) was established, to study the changes of these populations in the presence of competitors, prey, and the lamprey as invasive alien species. Then, the trend was observed respectively under the condition of sufficient and insufficient available resources, then extracting the change of the sex ratio of lampreys with the available resources. Its change curve is fitted then. Based on the EGD model and the sex ratio change curve, a comprehensive assessment system was established to comprehensively evaluate the specific impact indicators of the sex ratio of the lamprey on the ecosystem, and give relevant conclusions. It is expected that the model and system can be used to regulate the sex ratio of the lamprey by adjusting the available resources in different environments, to guide the management and regulation of the lamprey.

2. Sex Ratio Effects in the Lamprey

2.1. EcoGenderDynamics Model

This paper constructed the Eco Gender Dynamics Model based on the Lotka-Volterra model [9] to describe the interactions of lamprey populations with ecosystems, and ultimately to assess the effects of sex ratio changes on ecosystems [10]. A simple ecosystem model using the Great Lakes was constructed as an example, including three representative organisms, i.e. hosts parasitized by the sea lamprey and competitors that differ in growth rate and ecological niche [11]. To reflect changes in sex ratios and their dependence on local resources, male and female population densities were analyzed separately. Here denoted t as the time indicator, $M(t), F(t)$ as the number of male and female species in the lamprey population, respectively, and $N(t)$ the total number of the lamprey. This study also introduced the density of populations of the hosts and competitors, counted as $P(t), C(t)$. The population composition of organisms in this ecosystem is shown in Figure 1.

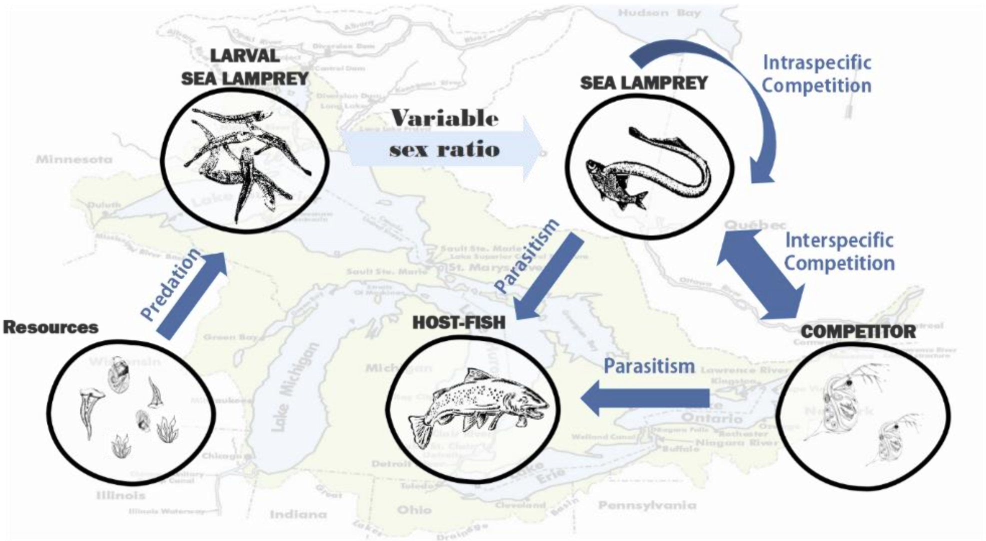

Figure 1. Basic components of the Great Lakes ecosystem

Hence the ordinary differential functions for prediction are listed as follows:

$$\begin{cases} \frac{dM}{dt} = \alpha_m M(1 - \frac{M}{K} - \frac{r_{l,c}C}{K_l} - \beta_M M + p_{l,p}MP) \\ \frac{dF}{dt} = \alpha_f F(1 - \frac{F}{K} - \frac{r_{l,c}C}{K_l} - \beta_F F + p_{l,p}FP) \\ \frac{dN}{dt} = \frac{d(M+F)}{dt} \\ \frac{dP}{dt} = \alpha_p p(1 - \frac{P}{K_p}) - pNP \\ \frac{dC}{dt} = \alpha_c(1 - \frac{P}{K_c} - \frac{r_{l,c}N}{K_c}) \end{cases} \tag{1}$$

Where, α_i is the growth rate of species i, β_i is the death rate of species i, k_i is the environmental carrying capacity of species i, r_i is the relative competitiveness between species i and j, p_i and is the parasitism rate for species i to species j.

To obtain the pattern of species change over time, a numerical scheme was needed to explain how they evolve in the short and long term. As this is a first-order ordinary differential system, with no higher-order terms or high-dimensional grids, the traditional finite differential method for solving the system numerically was applied.

2.2. Growth and death of the sex-shifting fish

According to data from the Great Lakes Fisheries Commission (GLFC) and its control agencies, Fisheries and Oceans Canada (DFO) and the United States Fish and Wildlife Service (USFWS), it can be seen that the sex differentiation ratio of sea lampreys is limited by food availability, and the proportion of male sea lampreys is larger in environments with lower food availability [12]. The proportion of males in the sea lampreys is always slightly more than 0.5 in realistic situations, and the sex ratio does not vary significantly with water hardness, pH, or latitude [13-14]. Therefore, a growth rate for the lamprey population that varies with resource availability was defined. Here, the total amount of resources, $S(t)$ and the average resource utilization rate, $R(t)$ are introduced. The growth rate r_f of female sea lampreys is positively correlated with $R(t)$, and the growth rate of male sea lampreys r_m is negatively correlated with $R(t)$. The growth rate of female sea lampreys is expressed as follows.

$$\begin{aligned} &\frac{dS}{dt} = -(a_s M + 2a_s F) \\ &R(t) = \frac{S(t)}{N(t)} \\ &\alpha_m = \alpha_{M_0} \times \left(1 - \frac{R(t) - satiety}{R(t)}\right) \\ &\alpha_F = \alpha_{F_0} \times \left(1 - \frac{R(t) - satiety}{R(t)}\right) \end{aligned} \tag{2}$$

Where, N is the total density of populations, α_{m0}, α_{f0} is the basal growth rate of the sea lamprey, a_s is the rate of reduction of the resource, and satiety is the upper limit of the average resource utilization rate $R(t)$.

The mortality rate of the species is considered by combining the effects of body size and human fishing activities. It is known that male sea lampreys are smaller in size (length and weight) than female sea lampreys at the same life span, and therefore have a higher mortality rate [15-16]. The prey situation of sea lamprey is ignored here, because in the natural environment sea lampreys have no natural predators [17], and are generally only preyed upon by humans, and sea lampreys make up only a small portion of the diet of a very small percentage of the population [18] (coastal indigenous tribes).

Temperature and humidity are assumed to be consistent and optimal for the growth and reproduction of each sea lampreys, in other words, resource availability is the only factor considered. At the same time, the upper river and the lake were considered as the same ecosystem and no mortality of sea lampreys occurs during geographically altered migration [19], i.e., the growth and mortality of non-parasitic larvae and parasitic larvae remain consistent [20]. Other parameters set in this simulation experiment are shown in Table 1.

Table 1. Attributes and Parameter Set for module

r_m	r_f	a_s	b	$satiety$	β_m	β_f
0.07	0.05	0.001	0.2	2.5	0.011	0.01

*The above parameters are all relative values.

2.3. Interspecific relationships between sea lamprey and other species

Given the large diversity of organisms in the Great Lakes ecosystem, to analyze the impact of the sea lamprey on the ecosystem, there is a need to focus on the interspecific relationships in the ecosystem. To make the model more discussable, this study chose the growth stage of parasitic larvae that have just migrated to the lakes as the time zero point and introduced two species in other ecological niches within the ecosystem to simulate a complex competitive environment.

In Great Lakes lake waters, the sea lamprey parasitizes large numbers of lake trout, lake whitefish, and cisco and can be considered an invader [21-22]. In this paper, the sea lamprey is an exotic invasive species with low initial densities, balanced sex ratios, and more abundant initial food resources. Here, this study chose trout as the only parasitized species within the environment (host-fish) and spiny water flea(competitor), which is also parasitized on trout, as the only competitor, and assumed that it enters the ecosystem at the same time as the sea lamprey, competing together for a patch of habitat but not sharing the same food resources. It is assumed that in this experiment, all three species have the same environmental holding capacity, and no other species are related to them, i.e., only their interactions under certain environmental conditions are considered.

Assuming that the relative competitiveness of organisms in an ecosystem is positively related to the proportion of biomass of the species in the ecosystem, the intra-species relative competitiveness and inter-species relative competitiveness of the counting sea lamprey are r_{ll}, r_{lc} respectively, and their expressions are as follows.

$$\alpha_C = \frac{C}{N+C} \qquad \alpha_N = \frac{N}{N+C} \tag{3}$$

Secondly, according to the information from [23], the sea lamprey and host-fish parasitism have a certain success rate.

$P = Attack\_rate * Pierce\_rate * Lethality\_rate = 0.00065$

The model parameters were determined in Table 2.

Table 2. Attributes and Parameter Set for module

a_c	α_p	K_c	K_p	K_l
0.055	0.02	50	50	50

*The above parameters are all relative values.

3. Results and Disscussion

3.1. Evaluating Ecosystem Dynamics

To obtain the relationship between sex ratio and food availability, the simulation results were used to fit the variables and obtained the expression of the function of sex ratio and resource availability as:

$$sex\_ratio = e^{-0.6800 + 0.1412/R} \tag{4}$$

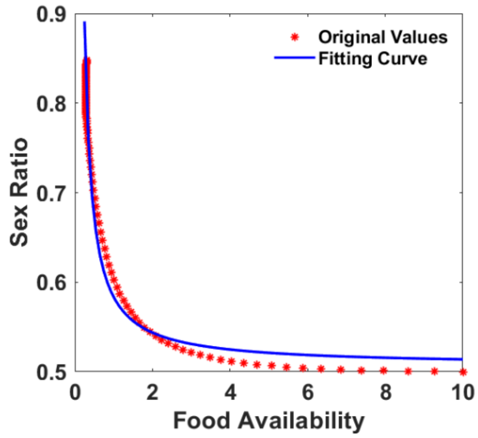

Figure 2. Fitting Function of Food Availability and Sex Ratio

Here the regression equation and the probability P-value of each regression coefficient are approximated to 0, which is less than the significance level of 0.05, and the goodness of fit R-sq is 0.9693, which shows that the model is well fitted to the data.

When comparing and embedding this function with the recent seven years of lampreys data provided by Global Biotic Interactions, the results were consistent with the rule. It is further proved that the function model is suitable for lamprey species and has guiding significance for predicting and controlling the growth degree and sex ratio of the lamprey population.

3.2. Sex_Ratio-Species Relationship

Here, the first assumption is that the growth and mortality rates of each species remain constant and that the relative competitiveness of species is the only factor considered. The interference factors such as gene mutation and water quality were weakened, and their influence factors were reduced to less than 0.01. The initial value of population density was given as The simulating result is shown in Figure 3.

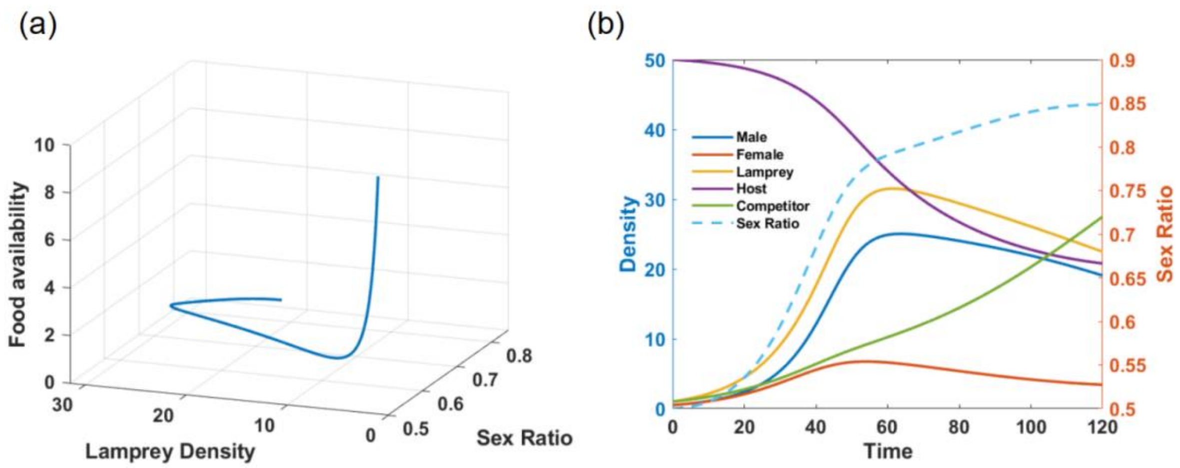

Figure 3. (a) Changes in Population Density and Sex Ratio and Sex Ratio-Resource; (b) Availability-Population Density Relationships during Biological Evolution.

By analyzing the above trends in population densities and the sex ratio of sea lamprey, significant conclusions can be drawn as the following:

(1) The population density of sea lamprey shows an increasing trend when there are adequate resources, with an average increase of about 2.5% per unit time. With time, the food shortage gradually occurred. When the average resource utilization rate was lower than 83% of the stability of each lamprey, the proportion of male sea lamprey increased significantly, from 52% to 76.4%, and then slowly increased and became stable. The density of sea lamprey shows a decreasing trend over time.

(2) Host population densities decline significantly as a result of the invasion of the sea lamprey, but don't die out, but eventually stabilize at a lower density level, falling to 44% of the initial total.

(3) Competitors were not dominant in the competition at first and began to dominate when the competitiveness of the population declined due to a gradual shortage of food for the sea lamprey, which led to the overall decline of the lampreys population at an average rate of 1.13% per unit time, and eventually to stabilize.

3.3. Competitive relationships of the sea lamprey

As it turns out, it can be seen that the growth rate of sea lamprey is affected by external environmental conditions, and the growth rate determines their sex. In an environment where food availability is low, the sex ratio of sea lamprey will favor males. At this time the reproduction rate within the population decreases and competitiveness is reduced. In addition to this, a review of the literature shows that fish in the Great Lakes have not co-evolved with the sea lamprey and cannot tolerate a parasite of this size, and most fish are attacked by the sea lamprey. The simulations are consistent with this fact. This suggests that sea lamprey, which can change the sex ratio of their populations in response to the external environment, is having an impact on the local ecosystem. The sex ratio and host and competitor population densities are shown in Figure 4.

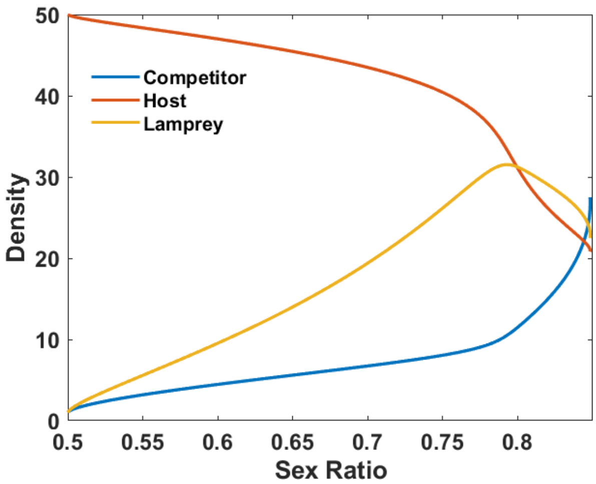

Figure 4. Changes in Population density with sex Ratio

The conclusions can be drawn as the following:

(1) As the proportion of males increases, the population density of sea lamprey first increases to the peak (about 31 units of measurement) and then decreases, this is because sea lamprey as an exotic species initially grows fast and the population density increases, but when the sex ratio seriously deviates from the equilibrium value, sea lamprey grows slower and reproduces less, so the population density decreases as a result.

(2) For hosts, a severe imbalance in the sex ratio of sea lamprey (above 0.78) will slow the decline in host population density.

(3) For competitors, an imbalance in the sex ratio of sea lamprey reduces their relative competitiveness, and competitor population densities increase rapidly to the point where they

outcompete the sea lampreys and gain a competitive advantage, with its growth rate increasing by 2.5 percentage points per year.

From the comparison between prediction data and actual data, the BP neural network has better prediction performance and relatively small error, which can meet the demand completely, and has fast prediction speed and convenient operation.

3.4. Robustness test of the model

To test the robustness of the model, normally distributed noise was added to all the given parameters in the model to simulate the uncertainty of nature and make the model more relevant to the real situation. The simulation results after adding randomness to the model are as Figure 5:

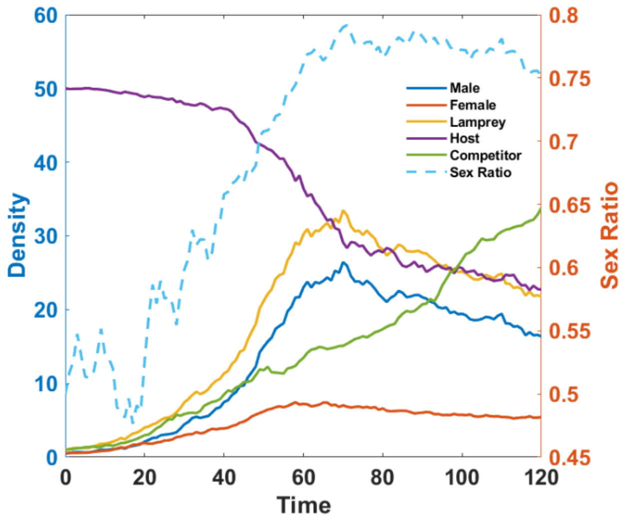

Figure 5. Simulation Results after Adding Normally Distributed Noise

Although the curve produced obvious fluctuations, the overall trend is still consistent with the above, which can fully prove the robustness and persuasiveness of our model. The influence factor coefficients of calculated perturbations can be as low as 0.12. Based on the above simulation results, it can be speculated that when the sea lamprey changes its sex ratio, it will have different impacts on other species within its population as well as in the ecosystem.

3.5. Eco evaluation system

Based on the EcoGenderDynamics Model, this paper considered two levels of Biological Interactions and Intrinsic Characteristics in this ecosystem, from which three indicators are selected as the basis for evaluating the dominance and weakness of the populations[24], as shown in Figure 6. Changing the sex ratio of the population, the values of each indicator are analyzed hierarchically to obtain the final scores and compare.

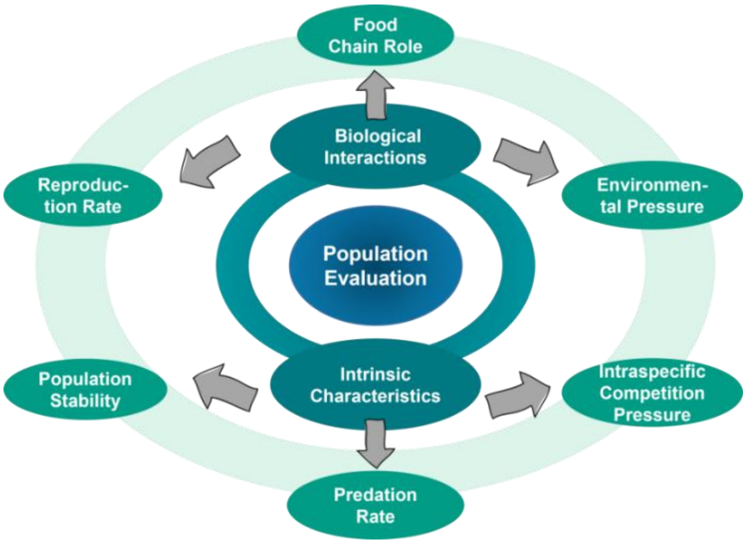

Figure 6. Eco evaluation system

Here chose two initial scenarios of scarcity of resources and sufficiency of resources, and three sex ratios for each scenario to simulate, as shown in Figure 7, to compare their scores.

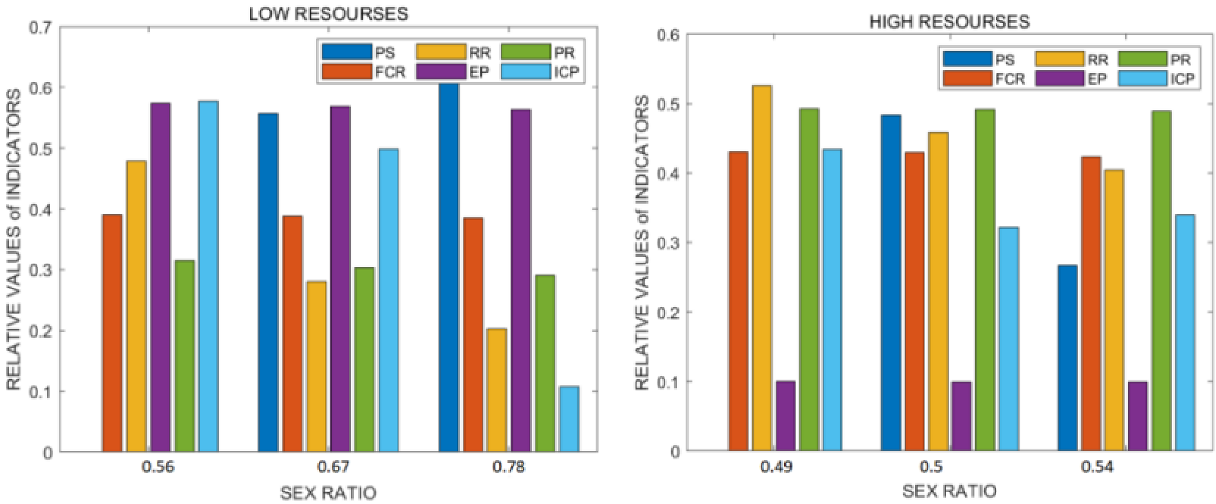

Figure 7. Local Stability across Resources and Gender Ratios

Using the AHP to comprehensively assess various indicators of the lamprey population's strengths and weaknesses, it can be observed that in inadequate resource areas, the lamprey population is more capable of leveraging its competitive and predatory advantages, resulting in higher scores. However, even in Insufficient resources situations, lampreys can still improve population stability by adjusting sex ratios through mechanisms, enabling them to achieve a certain balance with the environment through a form of "showing weakness". The ability to alter gender ratios is crucial for their survival.

4. Conclusion

This study reveals that sea lampreys exhibit a male-biased sex ratio in low food availability environments, impacting their reproduction rate and competitiveness. An extreme sex ratio imbalance (above 0.8) can paradoxically increase the competitiveness of other species, potentially allowing them to outcompete lampreys. The research considered two levels of biological interactions and six indicators to assess the sea lamprey population's strengths and weaknesses, finding that while ample resources enhance their competitive and predatory edge, limited resources prompt a strategic sex ratio adjustment. This mechanism allows sea lampreys to maintain environmental equilibrium, underscoring the significance of sex ratio flexibility for their survival.

This study provides a research idea and framework applied to the field of ecology, which can provide a new idea for the management and control of lampreys in the micro sense. And from the macro sense, it is convenient for us to study the interaction between lake ecosystems and organisms in the future. Through simulation and index evaluation, the feasibility of the method was proved.

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