

Research on the Impact of Lamprey's Sex Ratio on Ecosystems Based on the Lotka-Volterra Model

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Abstract: The aim of this study is to explore the impact of the population of the Lamprey on the ecosystem, particularly through the regulation of sex ratio, in order to provide effective strategies for environmental control. The study first improved the traditional Lotka Volterra model by introducing predator-prey relationships and environmental limiting factors. A Lotka Volterra predator environment model was established, and the stable environment of lampreys and their parasitic fish was simulated using this model. The results indicate that lower gender ratios (male population/overall population) can cause greater harm to the environment. The change in gender ratio can help control the food chain and may also exacerbate resource competition. Further integrating the relationship between gender ratio and growth rate into the Lotka Volterra predator environment model to form a gender Lotka Volterra predator environment model, the study found that a smaller gender ratio can lead to a decrease in ecological stability. When the gender ratio reaches a critical value, the ecosystem collapses. In addition, a dynamic ecosystem model was constructed for five species of organisms, including lampreys and parasites. Simulation results showed that reducing the sex ratio of lampreys can inhibit parasites and promote the prosperity of other organisms. The model has high robustness and stability. This study indicates that by regulating the sex ratio of lampreys, their impact on the ecosystem can be effectively controlled, providing a feasible environmental intervention strategy.

Keywords: Lamprey; Lotka-volterra; Ecosystem Dynamics Mode; Gender Ratios; Lotka-Volterra Model.

1. Introduction

The balance and stability of ecosystems are among the central issues in the field of environmental science. Among the many influencing factors, the sex ratio of species has garnered significant attention due to its profound impact on population dynamics and genetic diversity. This study focuses on an ancient and unique freshwater fish, the Lamprey, to explore the potential impact of its sex ratio on ecosystems [1, 2].

Traditional ecological models, such as the Lotka-Volterra model, provide a foundational framework for understanding the dynamics between predators and prey [3, 4]. However, to more comprehensively reflect the impact of changes in the sex ratio of lampreys on the environment, it is necessary to improve upon these models by incorporating predator-prey relationships and environmental limiting factors. This study first improved the traditional Lotka-Volterra model by introducing these factors and established a Lotka-Volterra predator-environment model that includes the Lamprey and its parasitic fish, simulating their survival status in a stable environment.

Furthermore, we constructed a dynamic ecosystem model that includes Lamprey and parasitic organisms among five species[5]. The simulation results indicate that reducing the sex ratio of lampreys can suppress the growth of parasites and promote the prosperity of other organisms. The model demonstrates high robustness and stability.

2. Simulation of the Dynamics of Lampreys

2.1. Presentation of Simulation of the Dynamics of Lampreys

In order to comprehensively reflect the impact of changes in the sex ratio of lampreys on the environment, it is necessary to establish a relatively complete system to simulate the interaction between lampreys and the environment. Therefore, it is necessary to consider the impact of changes in the sex ratio of lampreys on competitors, prey, and predators of lampreys. The correlation of environmental adaptability between lampreys and other species and their impact on the environment are shown in the table 1. According to table 1, there are very few predators in nature that feed on lampreys and can be almost negligible. Moreover, as an invasive species, the competition between lampreys and other species can also be ignored. Therefore, this study only considers the predatory relationship between lampreys and other species.

Table 1. Analyzing the correlation between the adaptability of lampreys and other species to the environment and its impact on the environment

Influence weight	Food chain	Destruction of habitats	Resource plunder	Ecological balance
Lamprey	0.65	0.53	0.63	0.54
Small mouth ell	0.21	0.14	0.22	0.3
Snake ell	0.14	0.33	0.15	0.16

This article first establishes a basic mathematical model to describe the relationship between species 1 and species 2,

which is based on the elimination of important variables. Assuming species 2 is a predator and species 1 is a predator. Without considering predation, it can be assumed that the growth rate of species 2 is directly proportional to the current population size. This article uses to represent time and represents the number of species 2. Therefore, the hypothesis about the increase in the number of species 2 can be expressed using the following equation.

Population growth can be expressed as follows:

$$\frac{dN_2}{dt} = r_2 N_2, r_2 > 0 \quad (1)$$

Among them, r_2 represents the growth rate of species 2. However, without considering predation, predators without food sources will become extinct. Therefore, the growth of predators can be represented by the following equation:

$$\frac{dN_1}{dt} = -r_1 N_1, r_1 > 0 \quad (2)$$

Among them, $N_{(t)}$ represents the number of species, r_1 represents the growth rate of species 1. Next, considering the predator-prey relationship between species 1 and species 2, this paper introduces the variable S to represent the predator's predation rate or the mortality rate of the prey. Considering that the growth of species is also limited by the environment, a saturation value K that is limited by resource conditions is introduced. Considering the simplest case to satisfy these properties, this paper introduces $(1 - N/K)$ to reflect the impact of environmental limitations on species. Therefore, the improved Lotka Volterra model is:

$$\frac{dN_1}{dt} = \alpha N_1 N_2 - r_1 N_1 \left(1 - \frac{N_1}{k_1}\right) \quad (3)$$

$$\frac{dN_2}{dt} = r_2 N_2 \left(1 - \frac{N_2}{k_2}\right) - \beta N_1 N_2 \quad (4)$$

Among them, β is the predation intensity of species 1; α is the predation intensity of species 1, K_1 is the environmental carrying capacity of species 1, and K_2 is the environmental carrying capacity of species 2.

According to Fig. 1, the growth rate of the Lamprey is relatively fast and it also competes with rapidly growing fish. The water environment itself is relatively small and cannot accommodate a large number of such organisms for survival. After a large number of fitting experiments, it is found that:

$$\frac{dN_1}{dt} = 0.0042 N_1 N_2 - 0.25 N_1 \left(1 - \frac{N_1}{10000}\right) \quad (5)$$

$$\frac{dN_2}{dt} = 0.20 N_2 \left(1 - \frac{N_2}{10000}\right) - 0.0004 N_1 N_2 \quad (6)$$

2.2. Gender Integrated Lotka Volterra Model

The gender change of lampreys has an impact on ecosystem stability, and gender ratio is integrated into the Lotka Volterra predator environment model. Add variable P as gender ratio and establish a relationship between gender ratio P and population growth rate r.

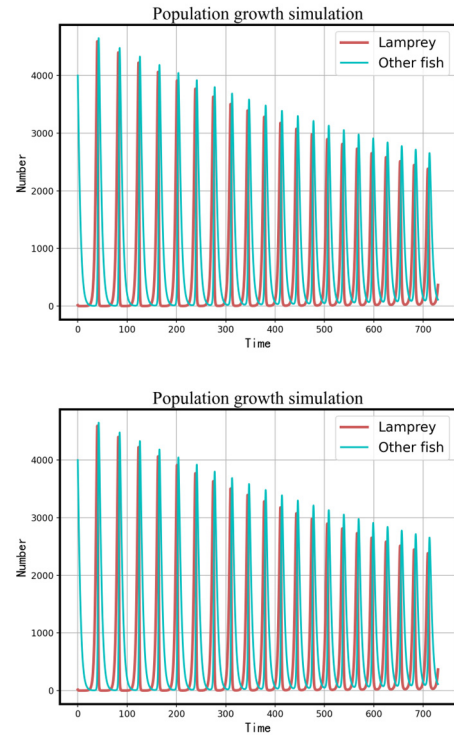


Fig 1. Line chart of growth rate of lampreys within one and two years under the same growth environment

Understand the relationship between sex ratio P and growth rate R, and obtain a large amount of sex ratio data and growth rate data of lampreys during the same period. After reviewing a large amount of literature, it was found that crocodiles and lampreys are two species living in similar aquatic ecosystems, both exhibiting temperature dependent sex determination mechanisms and adaptability to environmental changes. These two species inhabit warm tropical and subtropical regions and prefer aquatic environments such as rivers, lakes, and swamps. This article decides to replace the required data on lampreys with biological data with similar living environments and adaptive sex ratios. One of the key survival strategies is their gender ratio adaptability. During the incubation period, temperature gradients affect the gender of the new generation. High temperature environments tend to produce more female offspring, while low temperature environments facilitate the formation of male offspring. This gender adaptability allows crocodiles and lampreys to flexibly adjust their reproductive strategies to adapt to different ecological conditions, ensuring successful reproduction and maintaining a relatively stable sex ratio, promoting their survival and reproduction in their respective ecosystems. Therefore, the sex ratio data and growth rate data of crocodiles selected in the Five Great Lakes over the past 10 years were selected to observe the relationship between sex ratio and growth rate during the same period. And fit the obtained data, the curve fitting yields the following functional relationship:

$$r_1 = \frac{\ln\left(\frac{1-\rho}{0.734}\right)}{4.391} \quad (7)$$

Simulate the process of changing the P-value from large to small, and capture the quantitative relationship between the two populations in the early, middle, and late stages. The red line represents predators, and the blue line represents prey.

From the graph, we can clearly see that as the p-value, which is the gender ratio, decreases, the number of predators increases and the number of prey decreases. Even in the end, there is a sharp increase in the number of predators, and the number of preys sharply decreases to 0. The simulation results of population growth are shown in Fig. 2. The number of the two remains stable, and the stability of the entire system enters a dynamic equilibrium state, until the equilibrium is disrupted in the later stage.

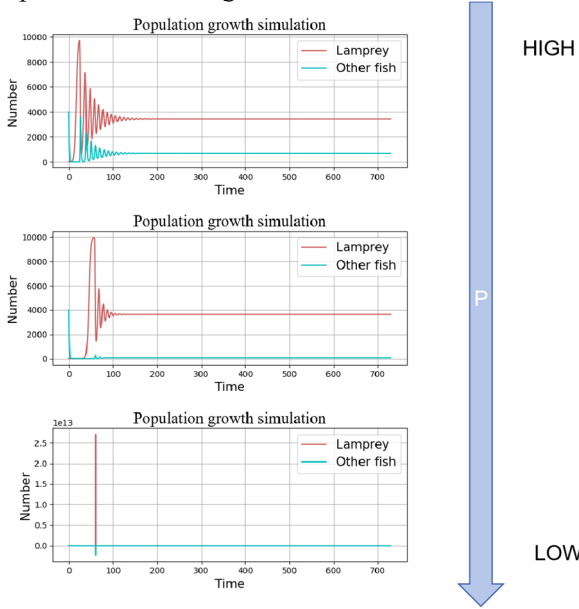


Fig 2. Line chart of the impact of gender changes in lampreys on the ecological environment

According to Fig. 2, it can be concluded that a gender ratio that is too small can seriously endanger the stability of the ecosystem. Only a moderate gender ratio can maintain ecological balance.

3. Ecosystem Model Centered on Lampreys

3.1. Presentation of Dynamic Model of Multi species Interactions

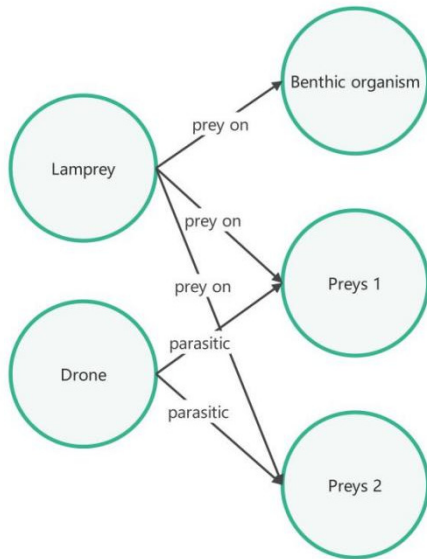


Fig 3. Multispecies Survival Relationship Diagram

To explore whether it can provide advantages for other

species in an ecosystem with variable gender ratios in the lamprey population. According to the multi-species survival relationship shown in Fig. 3, we chose to construct a dynamic ecosystem model with lamprey as the main research object. An ecosystem typically contains a large number of different species of organisms, from microorganisms to plants and animals, forming a complex and diverse biological network. Therefore, based on two population dynamic growth models, we take the lamprey as the main research object and consider the survival relationships between the lamprey and other species, including lamprey, two prey species, parasites, and benthic organisms. The ecosystem dynamic model has been simplified into a symbiotic network model that considers multiple aspects of predation or competition among species.

The interaction relationships between five species are as follows:

$$\begin{aligned}
 \frac{dN_1}{dt} &= r_1 N_1 \left(1 - \frac{N_1 + \alpha_{12} N_2 + \alpha_{13} N_3 + \alpha_{15} N_5}{K_1} \right) \\
 \frac{dN_2}{dt} &= r_2 N_2 \left(1 - \frac{N_2 + \beta_{21} N_1 + \beta_{24} N_4}{K_2} \right) \\
 \frac{dN_3}{dt} &= r_3 N_3 \left(1 - \frac{N_3 + \beta_{31} N_1 + \beta_{34} N_4}{K_3} \right) \\
 \frac{dN_4}{dt} &= r_4 N_4 \left(1 - \frac{N_4 + \gamma_{42} N_2 + \gamma_{43} N_3}{K_4} \right) \\
 \frac{dN_5}{dt} &= r_5 N_5 \left(1 - \frac{N_5 + \delta_{51} N_1}{K_5} \right)
 \end{aligned} \tag{8}$$

Among them, N_1 , N_2 , N_3 , N_4 , and N_5 respectively represent the population numbers of lampreys, prey 1, prey 2, parasites, and benthic organisms, and α_{ij} , β_{ij} , γ_{ij} , and δ_{ij} respectively represent the interaction coefficients between species.

3.2. Multispecies Modeling

The living conditions of lampreys under different competitive pressures and their impacts on ecological environment are shown in Fig. 4. When changing the growth rate of the two populations, the curve shape is also slightly different. We believe that the model is weakly sensitive to the parameters of population growth rate [6]. It can be seen that regardless of which party increases the population growth rate, it will shorten the evolution cycle of the model, accelerating the process of population growth and decline. When the ratio of their growth rates is approximately 1, the highest point of the two approaches, and as the ratio of rp/rg growth rates gradually decreases, the difference in the highest point between the lamprey and its prey also gradually increases. Meanwhile, when $rp/rg > 1$, it was found that the highest point of the lamprey did not exceed the highest point of its prey; When $rp/rg < 1$, lampreys may actually surpass their prey. This may be due to the fact that this phenomenon can be attributed to various complex ecological factors. Under high reproductive rates, although lampreys have high reproductive ability, they may be constrained by resource utilization efficiency, which may prevent them from effectively utilizing

high reproductive rates. On the contrary, under low reproductive rates, although the relative reproductive rate is lower, lampreys may be more effective in adapting to limited resources. Competitive relationships, population dynamics adjustments, and other environmental factors may also have an impact on this phenomenon. This suggests that when

studying food chain dynamics and species interactions, it is necessary to comprehensively consider multiple ecological factors, rather than just the ratio of reproduction rate to growth rate. Furthermore, as the values of r_p and r_g increase, the curve no longer exhibits periodicity but instead shows a state of amplitude decay over time.

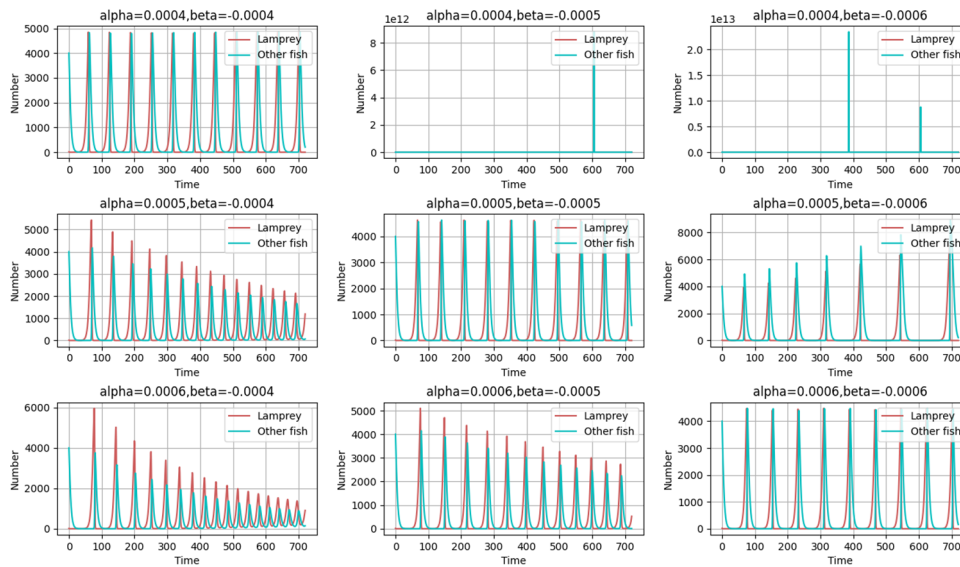


Fig 4. The living conditions of lampreys under different competitive pressures and their impact on the ecological environment

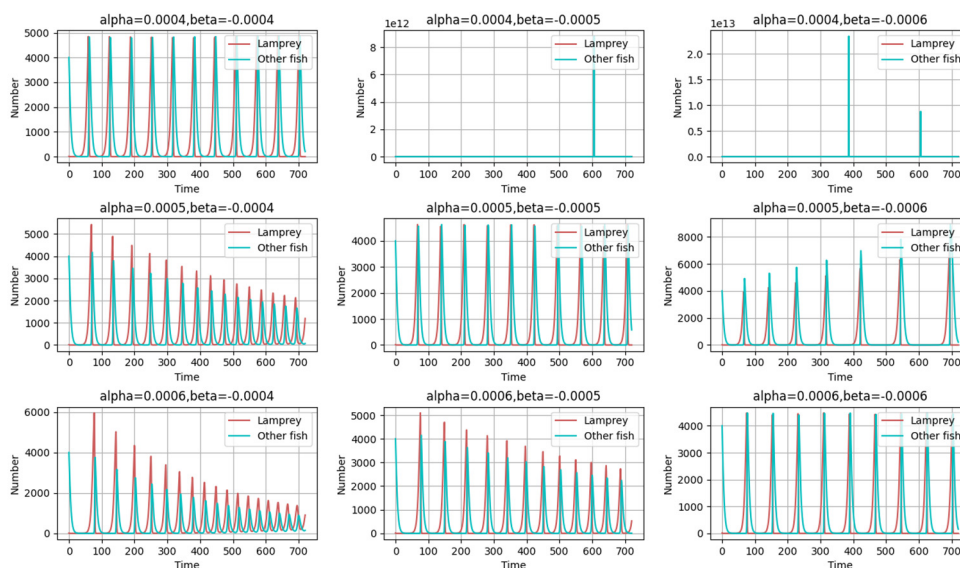


Fig 5. Growth status and environmental impact of lampreys under highly competitive pressure

According to Fig. 5, we believe that the model is highly sensitive to the parameters of the population competition coefficient. It can be seen that when $\alpha=0.0004$ and $\beta=-0.0005$ or -0.0006 , the model exhibits a gradient explosion phenomenon, resulting in unstable solutions. And when $\alpha > 0.0004$, the curve shows a state of amplitude attenuation over time, with the highest point of the lamprey surpassing its prey. The two exhibit a relatively regular periodic change, with the highest point of the lamprey being on par with its prey; When the amplitude of the time curve increases with time, it is beneficial for the reproduction of two species in the ecosystem, which is a

relatively ideal state.

3.3. Results of Dynamic Model of Multi Species Interactions

Through the experiment, we predicted the changes of different species in the same living environment for 120 days, and the results are shown in Fig. 6. As you can see from Fig. 6, the number of initial parasites is slightly higher than that of the population of lampreys, but over time, the number of lampreys gradually exceeds that of parasites, inhibiting the growth of parasite numbers. At the same time, the growth rate

of benthic organisms, prey 1, and prey 2 populations is gradually accelerating, while parasites parasitize prey 1 and prey 2, inhibiting the growth of both types of prey. Moreover, the time for prey 1, lampreys, and parasites to reach dynamic equilibrium is almost the same. This is enough to indicate that an increase in the population of lampreys can inhibit the growth of parasitic parasites, indirectly promoting the growth of both types of prey. Moreover, prey 1 and prey 2 have a similar effect on the growth of both types of prey. The interdependence between Lamprey and parasites is more pronounced, and it can be seen that the time when prey 2 and benthic populations reach dynamic equilibrium is almost the same. So it indicates that the species are interdependent and the model is effective. The conclusion drawn from question one can be seen that in the case where the sex ratio of lampreys can be changed, the number of lampreys is mostly in an increasing state, ultimately attributed to the mechanism by which lampreys can adaptively change their sex ratio. In such an ecosystem, the population of lampreys will inhibit the growth of parasite numbers, promote the growth of other organisms, and play an indispensable role in the stability of the ecosystem.

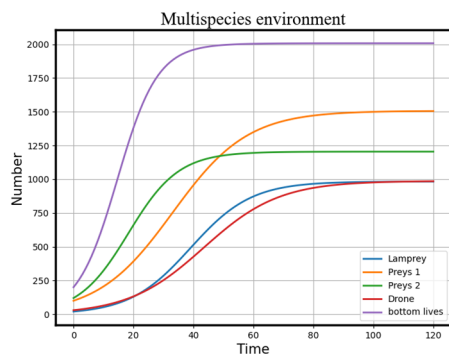


Fig 6. Simulate changes in various species under the same living environment for 120 days

4. Conclusion

The impact of lamprey populations on ecosystems is regulated through gender ratio, providing a method for environmental control. By incorporating predator-prey

relationships and environmental constraints into the growth rate model, we improved the traditional Lotka Volterra model and created a Lotka Volterra predator environment model. The simulation results of the model show that the lower the sex ratio (male quantity/total quantity) of lampreys, the greater the harm to the environment. The robustness of the model was verified through sensitivity analysis, and the results showed that the model is not sensitive to changes and has high stability and reliability. Furthermore, we incorporated the relationship between gender ratio and growth rate into the Lotka Volterra predator environment model, forming a new gender Lotka Volterra predator environment model. By constantly changing the gender ratio, research has found that the smaller the gender ratio, the poorer the stability of the ecological environment. When the gender ratio reaches a certain threshold, the ecosystem will collapse.

In summary, this study indicates that by regulating the sex ratio of lampreys, their impact on the ecosystem can be effectively controlled, providing a feasible strategy for environmental intervention.

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