Research on the Impact of Seven-Gill Lamprey Sex Ratio on the Ecosystem Based on the Logistic Model

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Keywords: Seven-gill lampreys; sex ratio; ecosystem; Logistic model; Lotka-Volterra model

Abstract: This study investigates the impact of the sex ratio of seven-gill lampreys on the ecosystem and explores analysis based on the Logistic model. It is noted that variations in the sex ratio can affect the lampreys' reproductive capabilities, thereby influencing their role in the food chain. The sex ratio is influenced by a variety of external environmental and biological factors, which affect the internal sex ratio of lampreys through natural selection and adaptive behaviors. To quantify the relationship between the sex ratio and external environmental resources, this paper employs the Analytic Hierarchy Process (AHP) and Python software to assess the impact of different external factors on the sex ratio. Furthermore, by constructing an improved Lotka-Volterra model, this paper analyzes the dynamic relationship between predators and lampreys and its effect on the sex ratio. The model considers the impact of the sex ratio on the reproduction and mortality rates and establishes differential equations for male and female lampreys separately. Simulations reveal that adjustments in the sex ratio significantly affect the reproductive success and social structure of populations. Finally, using the Logistic model, this paper quantifies the impact of changes in the sex ratio on the overall population growth rate, indicating that a sex ratio close to 1:1 results in the highest population growth rate.

1. Introduction

Ecosystems are intricate networks where each species plays a specific role and influences the balance of the entire system through various interactions [1]. The seven-gill lamprey, as an ancient and unique fish species, holds an undeniable position and function within freshwater ecosystems. However, the impact of sex ratio variations in lampreys on the ecosystem has not been sufficiently explored in ecological research [2, 3].

Sex ratio is one of the key factors affecting population dynamics and evolution. In many species, an imbalance in sex ratio can directly affect the reproductive success of populations and may also indirectly affect survival and reproduction by altering social structures and behavioral patterns [4]. Therefore, studying the variations in the sex ratio of lampreys and their ecological consequences is significant for understanding how species adapt to environmental changes and maintain ecological balance[5].

This paper aims to quantitatively analyze how changes in the sex ratio of lampreys affect their population dynamics and the ecosystem by constructing and applying mathematical models. We first explore the key biological characteristics and external environmental factors affecting the sex ratio of lampreys. Subsequently, we use the Analytic Hierarchy Process (AHP) and Python software to quantitatively analyze the external factors influencing the sex ratio [6]. Additionally, we propose an improved Lotka-Volterra model to simulate the interactions between predators and lampreys and their impact on the sex ratio. Lastly, we use the Logistic model to quantify the impact of changes in the

  DOI: 10.25236/iwmecs.2024.009

sex ratio on the overall population growth rate.

2. Sex Ratio Effect Analysis

2.1 Fundamental Biological Characteristics

To analyze this issue in greater detail, it is necessary to study the key factors influencing the changes in the sex ratio of lampreys, based on their physiological characteristics. Changes in the sex ratio can affect the overall reproductive capability of lampreys, consequently impacting their position within the food chain and their effects on other species. A bias towards a higher male ratio could decrease reproduction rates, which might impact the population size over the long term. Similarly, a lower reproduction rate could reduce the number of host species for parasites, potentially impacting parasitic species. The sex ratio of lampreys is primarily influenced by external environmental and biological factors.

How external environmental factors directly affect the growth rate of juveniles and ultimately determine their sex involves a detailed understanding of the changes in the internal sex ratio of the lamprey population. This includes how the sex ratio responds to changes in environmental resources and how these changes are optimized through natural selection and adaptive behavior within the population.

Therefore, a model is needed to quantify the relationship between external environmental resources and the sex ratio, and how adjusting this ratio can improve the survival and reproduction success rates of the population. Additionally, a quantitative assessment of the impact of changes in the sex ratio on other components of the ecosystem is required, considering how changes in the sex ratio affect the population's social structure, reproductive strategies, and interactions with other species.

To quantify the impact of different external factors on the sex ratio of lampreys, an initial step involves gathering comparative values from the literature, as shown in Table 1.

Table 1. Effect of different external factors on sex ratio of lampreys

factor	Water temperature	Competition for ecological niches	Contaminants	Habitat quality	Food availability
Water temperature	1	2	1/2	1/3	1/4
Competition for ecological niches	1/2	1	1/4	1/5	1/5
Contaminants	2	4	1	2	3
Habitat quality	3	5	1/2	1	2
Food availability	4	6	1/3	1/2	1

2.2 AHP

Next, the Analytic Hierarchy Process (AHP) is utilized to determine which factors significantly influence the changes in the sex ratio of lampreys, leading to the formation of corresponding pairwise comparison matrices. We employ Python software for the calculations, which enables us to specifically quantify the different parameters of how various external resources affect the changes in the sex ratio of lampreys. To sum up, the data in the table passed the consistency test and can be applied to the subsequent model.

Having identified the primary external environmental resources that influence changes in the sex ratio of lampreys, it is now necessary to construct a model to depict the impact of external biological factors on this ratio. From the literature, we understand the primary predators of lampreys, as shown in Table 2.

Table 2. Main predators of lampreys

Category	Specific organisms	account for
Larger Fish	Perch, trout, salmon, etc.	Large
Birds	Herons and cormorants	Medium
Humans	/	Smaller

Given the omnivorous nature of humans and the minimal part lampreys play in the human diet, our focus here is mainly on fish and birds preying on lampreys. A model is required to analyze the main relationships between predators and lampreys, and how predators affect the sex ratio of lampreys.

3. Establishment of Model

If lamprey populations could actively regulate their sex ratio, this ability could theoretically allow them to more flexibly respond to environmental changes and population pressures. However, this regulation also brings a series of complex ecological effects, including potential advantages and disadvantages. Specifically, the advantages include that increasing the female ratio when resources are abundant can help improve reproductive success rates; increasing the male ratio under resource scarcity can enhance competitive capabilities for resources. This can help populations adapt to environmental changes, such as habitat fragmentation and variability in food availability. Additionally, regulating the sex ratio can help manage genetic diversity and avoid inbreeding. The disadvantages include that extreme biases in the sex ratio might disrupt social structures and reproductive systems, leading to decreased reproductive behaviors and success rates. Uneven resource distribution could exacerbate internal competition pressure. Long-term reliance on sex ratio regulation might lead to adaptive traps, reducing the development of other adaptive behaviors. Furthermore, changes in the sex ratio could affect the balance of the entire ecosystem.

3.1 Lotka-Volterra Model

The Lotka-Volterra model, a classic predator-prey model, is apt for describing the interactions between two species, illustrating the dynamic changes of populations where one species is the predator and the other the prey. However, to incorporate changes in sex ratio, we need to modify this model to reflect such situations. Here, we will consider the population dynamics of lampreys, where the sex ratio can be influenced by external environmental factors. We will use the environmental factors from Table 1 to make simple modifications to the Lotka-Volterra model.

A modified Lotka-Volterra model is proposed, which takes into account the impact of the sex ratio on the reproduction rate and mortality rate of the lamprey population. Given that the Lotka-Volterra model traditionally considers the relationship of a species with its predators, and since male and female lampreys may be differently affected by external environmental and biological factors, we will treat male and female lampreys as separate populations and construct individual differential equations for each.

For male lampreys:

$$[\frac{dM}{dt} = r_M \cdot M \cdot \left(1 - \frac{M}{K_M}\right) - C_{M,T} \cdot M \cdot T]. \tag{1}$$

For female lampreys:

$$[\frac{dF}{dt} = r_F \cdot F \cdot \left(1 - \frac{F}{K_F}\right) - C_{F,T} \cdot F \cdot T]. \tag{2}$$

For primary predators of lampreys:

$$[\frac{dO}{dt} = r_O \cdot O \cdot \left(1 - \frac{O}{K_O}\right) - C_{O,T} \cdot O \cdot T]. \tag{3}$$

Using Python software and employing the Euler method for iteration, we address the initial value problem of ordinary differential equations. By incorporating the differential equation model that represents the dynamics of the lamprey population into Python, we are capable of simulating population changes under various resource conditions. As we can see from Fig. 1, this method adaptively adjusts the calculation step size, ensuring the accuracy and efficiency of the simulation. Thus, it aids in our understanding of how the availability of resources affects the sex ratio and its extensive impact on the ecosystem.

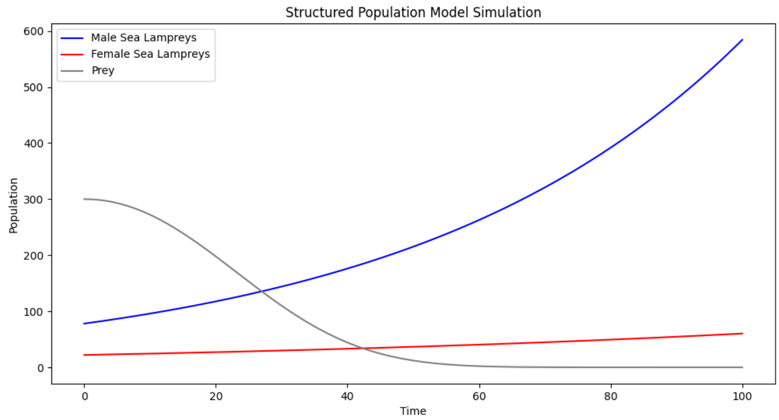

Fig. 1 Trends in other related species and in male and female lampreys

From the Fig. 1, it is observed that with an increase in iteration numbers, the population of female lampreys exhibits a slow growth, while the population of male lampreys grows more rapidly. The number of predators, on the other hand, continuously declines. When comparing horizontally, the population of male lampreys consistently surpasses that of female lampreys, and the number of predators gradually decreases to lower than that of both male and female lampreys. Based on the previously quantified indicators of external factors and the trend in changes to the sex ratio of lampreys, here we employ the principles of cellular automata for iterative simulation verification of the model. This approach better represents the processes of larval birth, growth, sex change, and the consumption and regeneration of food.Through dynamic simulation and visualization, this model can intuitively display the dynamic processes of complex systems, aiding in a deeper understanding of system behavior and patterns as shown in Fig. 2. Red indicates an empty cell where no organisms are present, green for females, and blue for males.

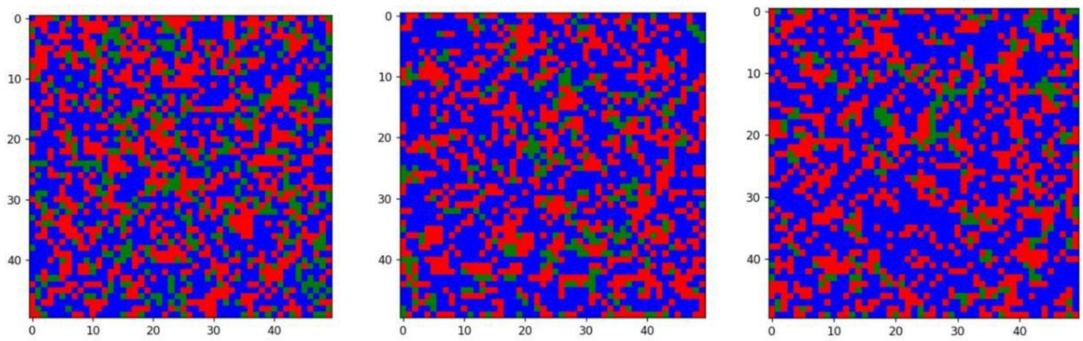

Fig. 2 Simulation of lamprey population change by cellular automata

3.2 Logistic Model

Here, we attempt to construct core equations to quantify these parameters (population growth dependent on density, environmental carrying capacity, etc.). We consider that the growth rates of female and male individuals are affected by the presence ratio of the opposite sex, meaning resource competition and imbalances in the sex ratio have a regulatory effect on growth rates.

The adjusted effective growth rate for each sex within the population can be defined as:

$$[\text{EffectiveGrowthRatefemale}=r_F \times (1\text{-f})]. \tag{4}$$

$$[\text{EffectiveGrowthRatemale}=r_M \times f]. \quad (5)$$

As such, the adjustment in the growth rate reflects the density-dependent assumption that as the proportion of individuals of the same sex increases, their growth rate decreases, and vice versa. The effective growth rate of the overall population can then be calculated by combining the effective growth rates of both sexes, and the overall growth rate after a weighted average is:

$$[\text{OverallGrowthRate}=(\text{EffectiveGrowthRatefemale}\times f)+(\text{EffectiveGrowthRatemale}\times(1\text{-}f))]. \quad (6)$$

We simulated and visualized the results using Python software to deduce the change in the overall population growth rate when the ratio of females to males changed from 0.1 to 0.9 as shown in Fig. 3.

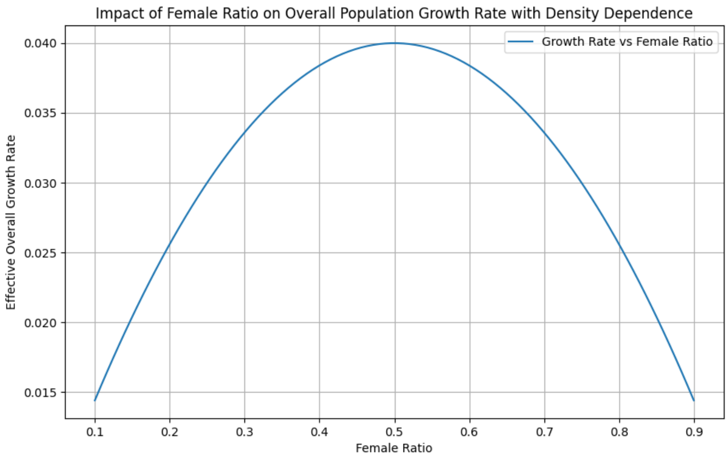

Fig. 3 The effect of changes in the ratio of male to female on population growth rate

3.3 Impact of Sex Ratio Variation on Population Growth

By simulating the population dynamics under different sex ratios, we can observe the trends in population numbers with fixed sex ratios. From the results obtained, the following analysis can be made:

1) Breeding Opportunities and Pairing Efficiency: The success rate of breeding is highly dependent on the pairing of males and females. When the sex ratio is close to 1:1, breeding opportunities are maximized, as nearly every female can find a mate. This higher efficiency in mate-finding leads to increased reproductive efficiency and a higher overall growth rate of the population.

2) Genetic Diversity: A sex ratio close to 1:1 also helps maintain genetic diversity within the population. Higher genetic diversity enhances the population's adaptability to environmental changes, reduces the likelihood of inbreeding, and indirectly improves the population's survival and growth rates.

3) Resource Competition and Behavioral Stress: In situations where the sex ratio is severely imbalanced, more intense internal competition may arise within the predominant sex, including competition for food, habitat, and reproductive resources. This internal competition can lead to uneven resource distribution, affecting the survival and reproductive capabilities of individuals of that sex, thereby lowering the overall growth rate of the population.

In summary, when the sex ratio is close to 1:1, the combined effect of these factors is conducive to maximizing reproductive success rates and efficient resource utilization, thereby enhancing the overall growth rate of the population. Conversely, when there is a large disparity in the sex ratio, the population faces increased challenges, including reduced breeding opportunities, intensified internal competition, and instability in social structure. These factors collectively lead to a decline in the population growth rate.

4. Conclusion

This study has illuminated the critical influence of the sex ratio on the population dynamics and ecosystem health of seven-gill lampreys. Utilizing mathematical modeling, we have determined that a balanced sex ratio is essential for optimal reproductive success and population growth. The research underscores the necessity of environmental and biological factors that contribute to maintaining this balance. Our findings advocate for conservation strategies that prioritize the sex ratio equilibrium, which is vital for the sustainability of lamprey populations and the ecosystems they are part of. The study's outcomes also stress the importance of interdisciplinary research in ecological management and conservation efforts.

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