

A Statistical and Machine Learning Based Study of Ecological Impacts in Lamprey

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Abstract. The aim of this study is to investigate the effects of changing sex ratios on ecosystems, with Lamprey as the subject of the study. It focuses on the impacts of changing sex ratios of Lamprey populations on their population size and ecological roles, and analyses their position in the food chain. Factors such as population size, sex ratio and growth rate of Lamprey were modelled and predicted through the development of the Lamprey Dynamic Model (LDM), incorporating relevant data analysis methods and mathematical models. Statistical and machine learning methods such as correlation analysis, Hermite interpolation algorithm, and Fourier fitting were used. The results showed that the sex ratio of Lamprey was closely related to environmental factors such as water temperature, oxygen content and water hardness. Through LDM modelling, the patterns of sex ratio effects on Lamprey population size and growth rate, as well as changes in its position in the food chain, were revealed. Positive and negative impacts of Lamprey populations on ecosystems were derived, including advantages such as adaptive sex ratio changes and reproductive migration strategies, as well as negative impacts of over-regulation of sex ratio and invasiveness on ecological balance. These findings provide new insights into understanding population dynamics and species interactions in freshwater ecosystems.

Keywords: Lamprey, Gender Change, Machine Learning.

1. Introduction

In recent years, the ecological impact of variable sex ratios on populations and ecosystems has become a focal point in scientific research. Understanding how changes in sex ratios influence population dynamics, species interactions, and ecosystem stability is crucial for effective conservation and management strategies. In this context, the study of Lamprey populations provides a unique and insightful perspective due to their adaptive nature and significant roles in freshwater ecosystems^[1-2]. The overarching question driving this research is how variable sex ratios in Lamprey populations affect their ecological dynamics and interactions within freshwater ecosystems. Lamprey, as a key species in aquatic environments, exhibits notable variations in sex ratios influenced by environmental factors. These variations can have profound effects on population size, growth rates, and interactions with other species, shaping the overall ecological landscape^[3].

To address these questions, our research follows a comprehensive approach. Firstly, we delve into the background of Lamprey ecology, highlighting their biological characteristics, habitat preferences, and ecological roles. This background sets the stage for understanding the intricate relationship between sex ratios and ecological dynamics in Lamprey populations. Secondly, we formulate specific research objectives to guide our investigation. These objectives include developing a Lamprey Dynamic Model (LDM) to simulate population dynamics based on sex ratios, analyzing the impacts of variable sex ratios on population growth rates, and exploring Lamprey's position within the food chain in relation to sex ratio variations^[4].

Our research methodology combines statistical analysis, machine learning techniques, and ecological modeling to achieve a holistic understanding of the topic. By integrating empirical data from field observations with advanced modeling approaches, we aim to uncover underlying patterns

and mechanisms governing the influence of sex ratios on Lamprey populations and their ecosystem dynamics. Overall, this study's significance lies in its contribution to the broader understanding of how sex ratio variability influences ecological processes in freshwater ecosystems, with implications for biodiversity conservation, ecosystem management, and sustainable resource utilization. Through a multidisciplinary approach and innovative methodologies, we seek to advance knowledge in this critical area of ecological research [5-6].

2. Impact of Variable Sex Ratios on the Ecosystem

In this section we will develop Lamprey Dynamic Model (LDM) to describe and forecast the population size of sea lamprey based on the changes of its sex ratios. As for the consideration of the effects on the ecosystem of a population that can regulate its sex ratio according to the environment, they should be divided into impacts on other living populations and the inorganic environment. The mind map is showing in Figure 1.

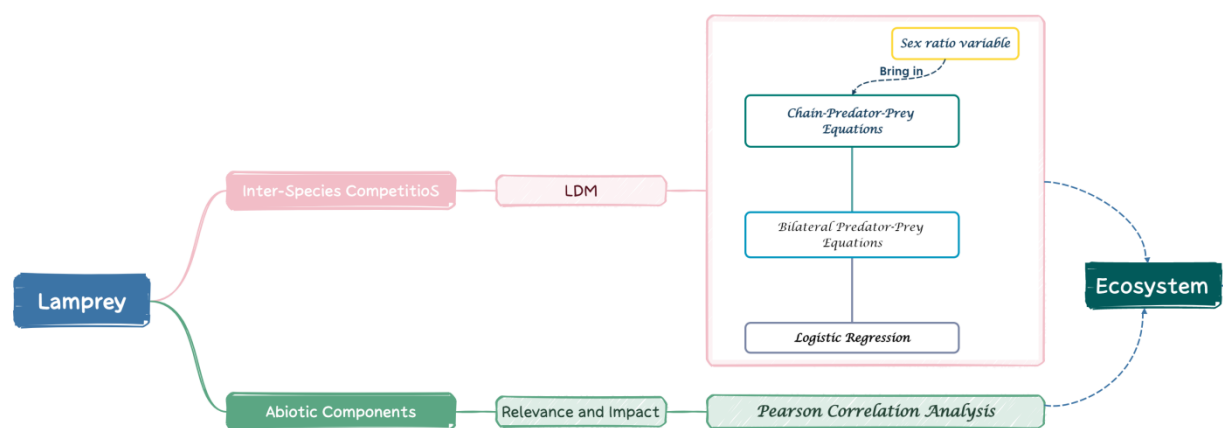


Figure 1: Our Work to the First Question

2.1. Abiotic Components

The abiotic component of watersheds is in constant flux. Abiotic factors that affect lake ecosystems include light, temperature, water pH, oxygen levels, and organic matter. Biological factors include bacteria, phytoplankton, aquatic plants, zooplankton, crustaceans, mollusks, in- sects, fish, and other vertebrates. When analyzing the impacts of sea lamprey, it’s important to separate the impacts of biotic and abiotic factors [7].

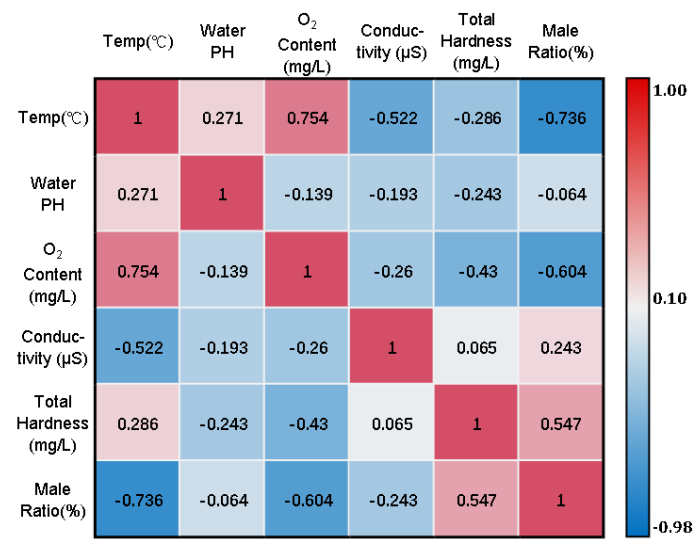


Figure 2: A correlation heat map

For research convenience, this paper selects relevant observational data from one of the Great Lakes in North America and combines it with existing research to identify a wide variety of abiotic components. The data that has been retained from the study includes information on temperature, water pH, oxygen content, conductivity, and total hardness which is weighed by calcium and magnesium ion content of the water in the lake. Correlation analysis of these parameters with the male ratio of sea lampreys in the Great Lakes has yielded a correlation heat map (Figure 2).

It is noticeable that the male ratio is negatively correlated with water temperature and oxygen content, with a strong correlation coefficient of greater than 0.6. On the other hand, water hardness is positively correlated with the male proportion of the sea lamprey population, with a correlation coefficient of 0.547. However, there is no correlation between water pH and conductivity and the male ratio of sea lamprey in the study area^[8-9].

Based on the preliminary analysis, it can be settled that the sex ratio (male:female) of the sea lamprey population size is strongly negatively correlated with the temperature of the water and negatively correlated with the oxygen content of the water. On the other hand, there is a general positive correlation between the sex ratio and the hardness of the water, while no significant relationship was found between water PH and conductivity of the water under the studied conditions^[10].

In order to study the sex ratio in the sea lamprey population size in a particular area, we analyzed three environmental parameters that showed strong correlations: water temperature, oxygen content, and total hardness. Then we combine and analyze these parameters to obtain a coupling function.

$$G = -1.089t_1 + 1.404t_2 + 2.529t_3 \quad (1)$$

That could help determine how these environmental factors affect the proportion of males in the population. The meaning of t_1 , t_2 , t_3 are displayed below.

- t_1 — Temperature of water in study region (°C);
- t_2 — Oxygen Content;
- t_3 — Total Hardness

2.2. Lamprey Dynamic Model (LDM)

2.2.1 Population size and Sex Ratio

The sea lampreys in the Great Lakes ecosystem play the role of invaders. During the study, we assume that the sea lamprey in the study area survives naturally, regardless of anthropogenic influences. Based on some of the data provided in the references, we preprocess the data by using the Hermite interpolation algorithm three times. We have found the best-fit curve equation with the R-square closest to one and a smaller RMSE using machine learning, and the data is approximately fits a Gaussian distribution. The fitted function is

$$f(x) = a_1 e^{-((x-b_1)/c_1)^2} \quad (2)$$

The coefficients are

$$a_1 = 241.5, b_1 = 46.73, c_1 = 18.64 \quad (3)$$

With 95% confidence bounds. And R-square of the result is 0.9415.

Using $N_{lamprey}$ represents the population size of lamprey in study area and p_m represents the male ratio of the lamprey population.

$$N_{lamprey}(p_m) = 241.5 e^{-((p_m-46.73)/18.64)^2} \quad (4)$$

R-square is greater than 0.9. That is to say, changes in population size explained 94.15% of the variation in sex ratio, which is a relatively good fit (Figure 3).

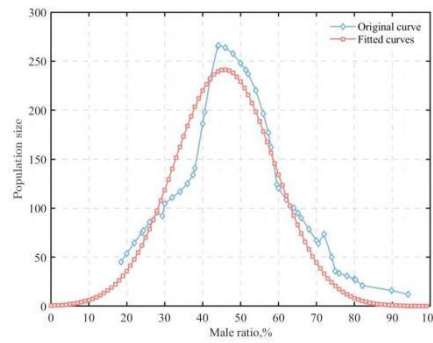


Figure 3: Fitted Curve of Population Size as a Function of Male Ratio

As can be seen from the figure, the population size of the sea lamprey population size in the study area reached its maximum at a male ratio near 0.45 for both the raw data and the fitted function. That is consistent with common ecological knowledge. Populations of organisms are more abundant when there is a slight edge of females in the population. Generally, this is the case when the environment is suitable, and resources are sufficient.

2.2.2 Growth Rate and Sex Ratio

The growth rate of sea lamprey in the study area is directly related to their population size, and the data were processed using that from the relevant waters in conjunction with supervised machine learning based on Fourier fitting. The core idea of the Fourier fitting principle is that any periodic function can be represented by a linear combination of a series of sine and cosine functions. In this case, it can be written as

$$f(x) = a_0 + a_1 \cos(xw) + b_1 \sin(xw) \quad (5)$$

The coefficients are

$$a_0 = -6.533e + 05, a_1 = 6.533e + 05, b_1 = -290.6, w = -1.9e - 05 \quad (6)$$

with 95% confidence bounds. And R-square of the result is 0.7917.

The following results are obtained as well as the fitted curve (Figure 4).

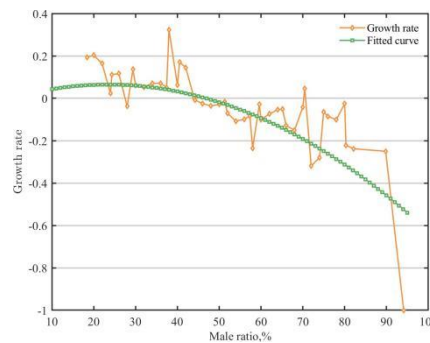


Figure 4: Fitted Curve of Growth Rate as a Function of Male Ratio

Put substitute parameters into the function then the further expressed as,

$$\varphi_{lamprey}(p_m) = \mathcal{F}_0 + \mathcal{F}_1 \cos((-1.9e - 0.5)p_m) - \mathcal{F}_2 \sin((-1.9e - 0.5)p_m) \quad (7)$$

When the male proportion of the lamprey population in the study area exceeds 90%, the natural growth rate of the population will change drastically. Considering that such a large proportion of males does not usually occur in natural environments, we chose the actual and fitted values of the male proportion between 20% and 90% to calculate the R-square and obtained the result of 0.7917. That indicates that the fitted function can describe the variation of the growth rate of the sea lamprey population in the study area with the proportion of males.

2.2.3 Sea Lamprey in Food Chain

In examining the interactions of sea lampreys with other organisms in the ecosystem, we narrow the scope to predator and prey populations closely related to sea lamprey populations. Rigorously, species that are preyed upon by predators of the same species are not always at the same trophic level, but for the sake of model simplicity, all populations of organisms that prey on sea lampreys, i.e., predators, were further categorized as being at the lower trophic level; and all populations of organisms that are preyed upon by sea lampreys, i.e., prey, were viewed as being at the upper trophic level. This allows for predator modeling based on the Lotka-Volterra equation.

Before building the model, the constraints of the model need to be clarified. So, we make the following assumptions to simplify the mathematical process:

In a closed and stable ecosystem, there are sufficient natural resources, and the carrying capacity of the environment is high.

The predator has a sufficient food source and is not affected by the effect of time.

The predator population relies solely on the energy intake of its prey for reproduction and other activities.

The rate of change in the population size of each species is proportional to the scale of its size.

There is no reason for the predator to give up its prey.

For grouping analysis, first establish bilateral predator-prey equations for adjacent trophic levels. For each group of predator P and prey Q, the change in population size of the two species over time will follow the following pattern:

$$dp/dt = \delta pq - \kappa p \quad (8)$$

In the set of differential equations, p is the number of predators; q is the number of preys; t is time; ϕ represents the natural rate of growth of the predator; ρ represents the efficiency with which the predator population feeds on its prey; κ represents the natural mortality rate of the predator; δ represents the increased survival rate of a given predator population as a result of feeding on its prey.

Numerical solutions of differential equations make graphs as Figure 5.

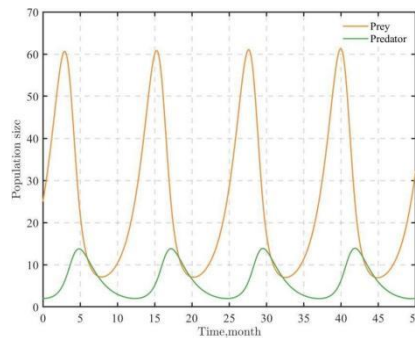


Figure 5: Fitted Curve of Population Size as a Function of Sex Ratio

The fluctuations in the graphs show the interdependence between predator and prey.

A third trophic level was further introduced to form a food chain consisting of at least three trophic levels, as shown in Figure 6. Continuing with the above assumptions to build chain- predator-prey equations, we transform the natural growth rate of the population size of the lamprey in the model to a function on the proportion of males in the lamprey population since the population can change the sex ratio according to the environmental adaptations.

$$\begin{aligned} dY_1/dt &= \phi_1 Y_1 - \rho_2 Y_1 Y_2 \\ dY_1/dt &= \rho_2 Y_2 Y_1 + Y_2 (\delta_2 + \phi_2 (p_m) - \kappa_2) - \rho_3 Y_2 Y_3 \\ dY_1/dt &= \delta_3 Y_2 Y_3 - Y_3 K_3 \end{aligned} \quad (9)$$

In the set of differential equations, Y1 is the number of the upper level of lamprey; Y2 is the number of lamprey; Y3 is the number of the next level of lamprey; t is time; ϕ represents the natural rate of growth of a species; ρ represents the efficiency with which a given predator population feeds

on its prey; κ represents the natural mortality rate of a given species; δ represents the increased survival rate of a given predator population as a result of feeding on its prey. Figure 6 shows a food chain that illustrates the model.

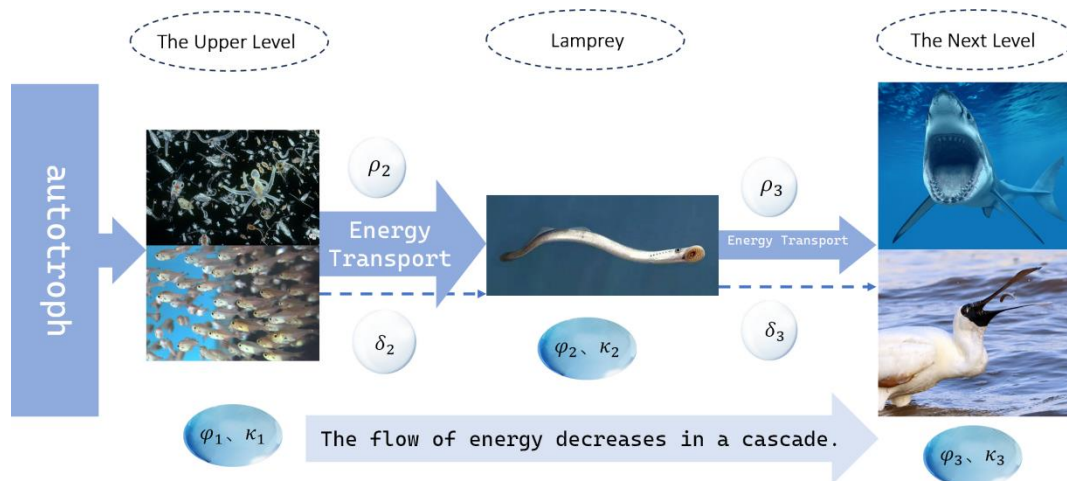


Figure 6: Food Chain

Using the above differential equations can explain the variation in the population size of the lampreys within the constraints of the model. Since the natural growth rate of the lamprey's population in the model is a function of the proportion of males in the population, which can represent the impact of environmental factors. Therefore, more dynamic information can be reflected on the basis that the population size of the lampreys shows a Gaussian distribution with the proportion of males.

2.3. Pros and Cons of the Lamprey Population

In an ecosystem, the benefits and drawbacks of biological populations are determined by their ability to access resources, compete for survival, adapt to changes, and maintain resilience. By examining how the sea lamprey population fares in these areas, we can gain insights into how ecological niches expand and how different species interact in a constantly changing ecosystem.

2.3.1 Pros of the lamprey population

Reproductive Migration

Sea lamprey populations return to streams to select high-quality environments for nesting and spawning, which improves offspring survival and reduces resource competition and stress. Their integrated use of resources in multiple waters also expands nutrient cycling, allowing populations to grow and develop stably. In addition, the diversity of breeding environments and methods can lead to mutations (gene mutation, gene recombination, chromosomal variation), thus increasing genetic diversity.

Adaptive Sex Ratio Variation

According to the LDM (Lamprey Dynamic Model) established, changing the sex ratio of the sea lamprey population in the study area, multiple population size dynamics curves can be obtained.

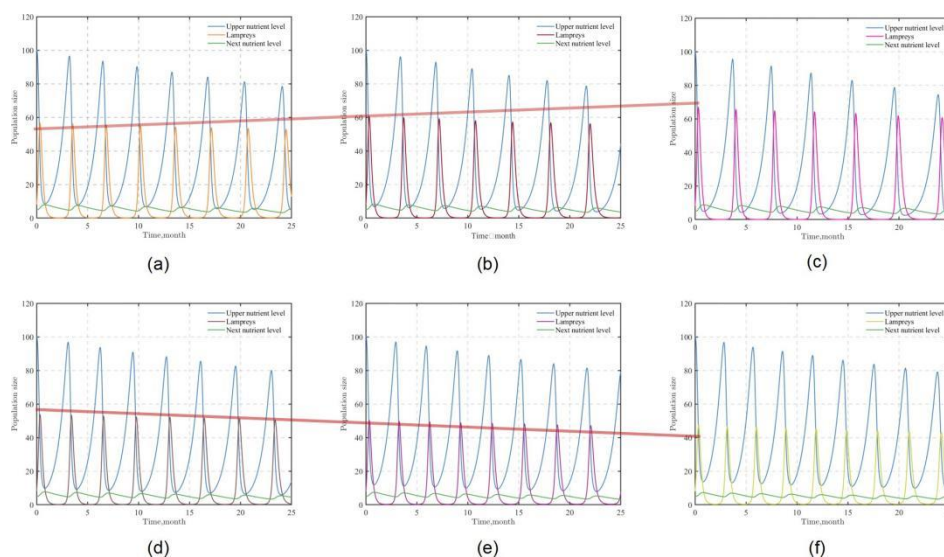


Figure 7: Population size changes with male ratio

Observing the curves (Figure 7) when the sex ratio (male: female) was 1:2.33, 1:1.5, 1:1, 1:0.67, 1:0.43, 1:0.25, respectively, we can see the trend of the population size of the sea lamprey by the sex ratio: the population size is higher when the male: female ratio is near 0.667. The environment is generally more suitable for the growth of the sea lamprey, along with sufficient resources. However, when the environmental conditions tend to be more difficult, then the survival rate of male sea lampreys, which are better in terms of survival ability and mobility, is higher, and the larvae tend to differentiate into males, which shows the male-biased sex ratio in the population, the population size decreases on the contrary. Enhancing population viability by sacrificing population size and reproductive capacity allows the lamprey population to remain as stable as possible for population sustainability.

Advantages in Physical Characteristics

The lamprey populations survive primarily by feeding on the flesh and blood of their prey, with sharp teeth and highly adsorbent mouthparts that can cling to the prey, often until it dies. Its spinal cord can be completely regenerated and is highly adaptable to the environment. That is one of the reasons it can be an invasive species.

2.3.2 Cons of the lamprey population

Over-Regulation of Sex Ratio

The process of sex ratio regulation in lamprey can occur when there are far more males than females in the population, a phenomenon we call over-regulation. When there are insufficient resources in a lamprey population, an overrepresentation of males may lead to increased species competition and inefficient mating. Continued differentiation of newborn larvae by male preponderance will lead to a continuous decline in population size. Eventually, the population will stabilize at a low level, putting the lamprey population at a disadvantage in inter-specific competition.

Disadvantages Arising from Ecosystem Self-Regulation

When the sea lamprey invading the Great Lakes is not under human control, its strong adaptive ability and aggressiveness will seriously disrupt the balance of the original ecosystem, thus affecting the abiotic factors in the ecosystem and the deterioration of the ecosystem and the scarcity of food resources will, in turn, constrain the development of the lamprey populations if the environmental conditions are not compensated for and repaired.

3. Conclusions

Our study provides insights into the effects of changing sex ratios on Lamprey populations in freshwater ecosystems. By combining empirical data analysis, statistical methods and ecological

modelling, we gained valuable insights into how changes in sex ratio affect population dynamics, growth rates and ecological interactions. These findings not only highlight the importance of sex ratio in ecosystems, but also provide guidance for future ecological management and conservation practices. Our study not only contributes to a better understanding of the ecological behaviour of Lamprey populations, but also makes an important contribution to maintaining the health and sustainability of freshwater ecosystems.

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