

The Role of Lamprey Sex Ratios in Ecosystem Dynamics: An Analysis Using Lotka-Volterra Models

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Abstract. With global ecological changes, studying the sex ratio of lampreys in ecosystems and their impact on the food chain and ecological stability has become a key topic in ecology and environmental science. Lampreys are found mainly in the North Pacific region and are considered to be parasites that have a significant impact on the ecosystem. The sex ratio of lampreys is not as 1:1 as in most species, depending on how quickly they grow during the larval stage. In response to this, this study started with the living habits of lampreys and studied the impact of different years in different watersheds on the sex ratio of lampreys, as well as the relationship between water temperature and catch quantity. Subsequently, the Lotka-Volterra model theory was applied to prove that the sex ratio of lampreys has a greater impact on ecosystems in simpler food chains, but a smaller impact in more complex food chains. This study successfully revealed when the population of lamps can alter its sex ratio, lampreys have a certain impact on the quantity and structure of species in ecosystems.

Keywords: Lotka-Volterra Model, Predator-Prey Model, Differential equations, food chain.

1. Introduction

With the rapid changes in the global ecological environment, species interactions within ecosystems and their responses to environmental changes have become a focus of current ecological and environmental science research. In this research field, the sex ratio of specific species and their impact on ecosystem dynamics are particularly noteworthy. Lampreys, as a species that plays a crucial role in the ecological food chain, its sex ratio has a significant impact on the predator-prey relationship in the ecosystem, thereby affecting the stability and function of the entire ecosystem.

For this study, this work started using the Lotka-Volterra model algorithm, and this model was first proposed by Lotka^[1] and Volterra^[2], now it has been applied in various fields. For example, there have been studies on the quantity and structure of organisms in lakes and rivers^[3,4], as well as the integration of this model with time delay properties^[5,6], the integration of this model with dynamics^[7-9], and related studies on the associative relationship of concepts based on Lotka-Volterra Predator-Prey Model^[10], etc.

In this work, this study first described the living habits of the lamprey, then visualized the lamprey's sex situation in the Lentic area and Rivers and the relationship between water temperature and captured quantity. Subsequently, this work simplified the food chain of the lamprey, treating it as a simple ecosystem model with the food chain of indigenous people, and the food chain of large and small fish as a complex ecosystem model.

2. Patterns and Influences in Lamprey Populations

2.1. The living habits of lampreys

Lampreys live in cold and mild waters. Some specifically live in freshwater, while others live in the ocean but migrate to freshwater to lay eggs. Some lampreys are parasitic, and these species live in freshwater or the ocean. Non-parasitic lampreys live in freshwater habitats.

2.2. The relationship between age and sex

To clarify the sexual orientation of lampreys after entering the mature stage, this study is based on the data from an article on the USGS website titled "Biodata, net catch, and detection records for juvenile sea sampled in natural streams in Michigan and Quebec Canada and an artificial stream at USGS Hammond Bay Biological Station during 2011, 2014-2015", and the experiments are conducted in five regions^[11]: Ford River, East August River, Pine River, Steeles Creek, and White River, where the coded wire-tagged larval sea lamprey was released. Then, the lampreys were recovered as adults in traps deployed through Lake Huron and Michigan.

After organizing the data, the Figure 1 shows the relationship between age and sex quantity in two different types of river basins. Among them, two different types represent "whether the stocking location was in Lakes Huron or Michigan near a stream mouth (lentic) or in a stream that flows into Lakes Huron or Michigan (river)" respectively, and year represents "the number of years that passed between when the larval sea lamprey was stocked to when the lamprey was recovered as an adult in traps deployed throughout Lakes Huron and Michigan".

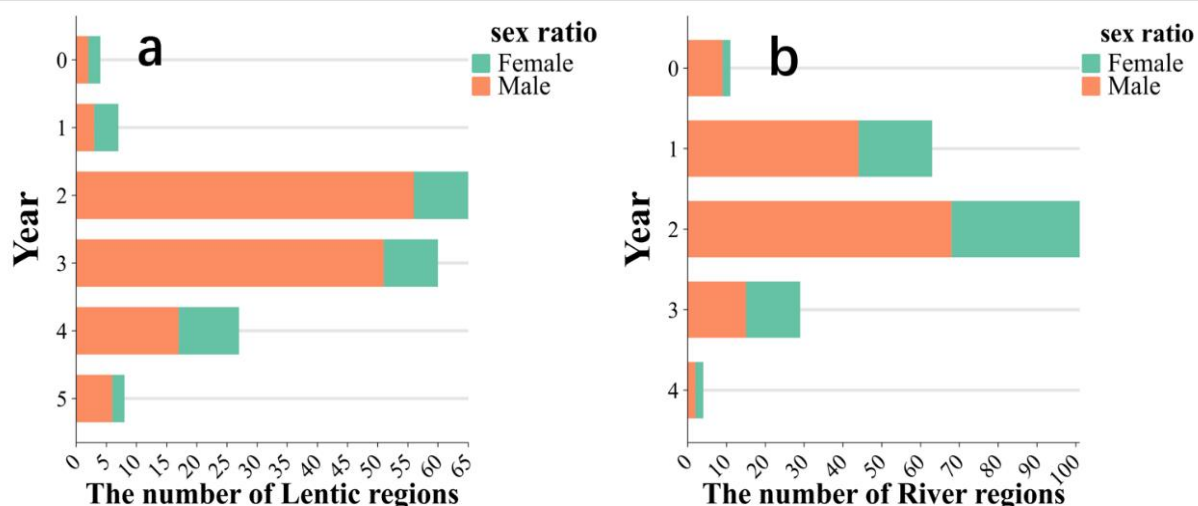


Figure 1 Lamprey's sex situation in the Lentic area and Rivers. (a) Lentic area,(b) Rivers.

By comparing different dimensions, this study can lead to the following conclusions:

1. In terms of quantity, lamprey has the highest number between the ages of 2 and 3, and the age range of 4 to 5 is almost the twilight stage of lamprey.
2. Regardless of the age group, the number of males is almost greater than females, especially between the ages of 2 and 3.
3. The proportion of males in the Lentic area is even more pronounced between the ages of 2 and 3 compared to the river, and it can be speculated that the sex ratio of Lamprey is influenced by water quality.

2.3. The relationship between temperature and capture quantity

This work noticed that the survival of lampreys is also related to the water temperature of lakes, so this study found a relationship between water temperature and being caught in lampreys. The experimental dates were from 11/1/2011 to 11/9/2011, and most lampreys were caught at night, the results are shown in Figure 2.

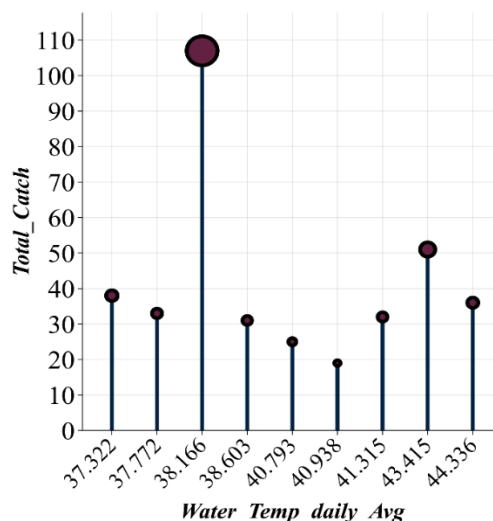


Figure 2 The Relationship between Water Temperature and Captured Quantity

This study can lead to the following conclusions:

1. At 38.166 degrees, the lamprey's total catch reached its maximum, and it can be speculated that 38 degrees is the optimal temperature for the survival of lampreys.
2. Overall, there is not much difference in the total number of lampreys between 37 and 44 degrees Celsius. It concludes that except for around 38 degrees Celsius, which is the optimal temperature, other temperatures have little effect on the survival of lampreys.

3. Lamprey Sex Ratios and Ecosystem Dynamics

This work needs to study the impact of lampreys on populations in ecosystems. The study can use changes in the number of prey and prey as indicators. Below, this work has established a relevant model and attempted to find the relationship between the male-to-female ratio and the corresponding population quantity.

3.1. The food chain of lampreys

To locate the position of lampreys in the ecosystem and simplify our food chain model, this study searched for their natural enemies and food and established a model to observe their population changes.

3.1.1 Enemies & food

The sex ratio changes of lampreys in ecosystems may affect their position in the food chain. Due to their different dietary habits and behaviors at different gender stages, changes in gender ratios may trigger adjustments in the food chain, affecting the survival and reproduction of other species. In addition, lampreys play a dual role as both predators and prey in aquatic ecosystems, which are vulnerable to natural predators such as large fish species, aquatic birds, and marine mammals, particularly during their spawning migrations. Furthermore, lampreys prey on smaller fish, aquatic insects, and invertebrates by attaching themselves to their hosts and feeding on their blood and bodily fluids. The lamprey's significant position in maintaining ecological balance and their interactions with other aquatic organisms are highlighted by their dual role in the food chain.

3.2. Establishing mathematical models

3.2.1 Lotka-Volterra model

This study can establish a model where the predation rates of female and male lampreys on different food sources and different natural enemies are different. In the natural world, there are many different interactions among populations of organisms, which may restrict or promote each other, and predation has been a hot topic of research in recent years. The predator-feeder model was first

proposed by Lotka, an American ecologist Volterra, and an Italian mathematician, and has attracted much attention since then:

$$\begin{cases} \frac{dx}{dt} = rx - bxy \\ \frac{dy}{dt} = -dy + cxy \end{cases} \quad (1)$$

Here $x(t)$ and $y(t)$ denote the density of the bait and the predator at the time t , respectively. The norm r is the intrinsic growth rate of the bait and d the mortality rate of the predator in the absence of the bait. b c and the mutual contact rates of the predator and the bait, respectively. To reflect the real mechanisms of different predator types, many scholars have improved and extended the original L-V model by incorporating many new and important ecological relationships and environmental factors, such as diffuse predation with different functional response functions. Diffuse predatory bait systems with different functional response functions.

Based on this, this work uses P_Female , which represents the proportion of females in the population, and P_Male , which represents the proportion of males in the population.

Some equations in the model can be represented as:

1. Predation on Food Sources:

For food type A:

$$\frac{da}{dt} = -P_f \cdot c_{a-f} \cdot a + P_m \cdot c_{a-m} \cdot a \quad (2)$$

For food type B:

$$\frac{db}{dt} = -P_f \cdot c_{b-f} \cdot b + P_m \cdot c_{b-m} \cdot b \quad (3)$$

2. Predation by Predators:

For the Predator X:

$$\frac{dX}{dt} = P_f \cdot c_{X-f} \cdot (a + b + c) + P_m \cdot c_{X-m} \cdot (a + b + c) \quad (4)$$

For the Predator Y:

$$\frac{dY}{dt} = P_f \cdot c_{Y-f} \cdot (a + b + c) + P_m \cdot c_{Y-m} \cdot (a + b + c) \quad (5)$$

Through this model, this work can adjust parameters (such as a , b , c) to simulate the impact of different sex ratios on the food chain, where the Lamprey food sources include three types of organisms a , b , and c . The Lamprey natural enemies include predators of types X , Y . Natural enemies of the Lamprey include three types of predators, X , Y , and Z . This model can be used to explore the impact of sex ratio changes on the interactions between lampreys and their food and natural enemies, as well as how these changes are transmitted to larger ecosystems.

3.3. Lampreys and Indigenous Peoples

3.3.1 Modeling process and the process of solving

Considering that lampreys are also a food source for some Indigenous peoples of the Pacific Northwest in North America, this work uses the Lotka-Volterra Predator-Prey Model to explore their related changes. This work sets initial values, such as the ratio of male and female lampreys, the number of indigenous people, etc., defines equations, sets simulation time, uses an ode45 solver for simulation, and then draws the results.

3.3.2 Programming results

This work sets the male ratio of lampreys to 0.56 to 0.78, with a step size of 0.01. After initializing the model parameters, Figure 3 shows the results of the changes in the number of lampreys and indigenous peoples under different male-to-female ratios.

Due to limited space, this work has provided results showing a male ratio of 0.56 and 0.78 for lampreys.

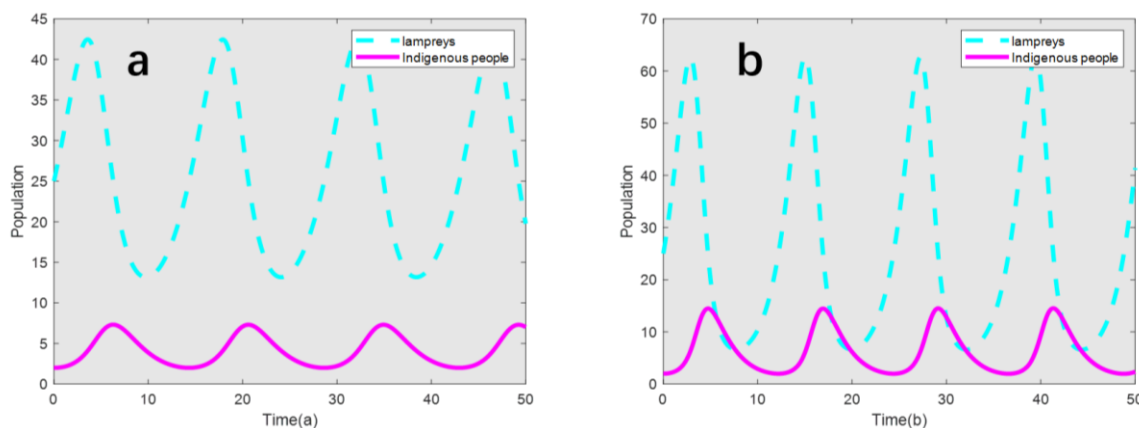


Figure 3 The quantity variation curve of Lampreys and Indigenous People.

The male ratio of lampreys: (a)0.56, (b)0.78.

The following conclusions can be drawn from the above research:

1. After comparing different images, it can be found that sex ratio can indeed affect the changes in the number of indigenous people, and Lamprey itself can also be affected.
2. There is a trade-off between lamprey and the number of indigenous people, which constrains each other.

3.3.3 The relationship between the maximum and minimum number of indigenous people and the sex ratio of lampreys

To explore the relationship between the sex ratio of lampreys and the number of indigenous people in more detail, this work corresponded the corresponding maximum and minimum number of indigenous people and the proportion of males throughout the entire time in the above image, forming a curve to find the corresponding pattern. The curve in Figure 4 shows the changes in the number of indigenous people.

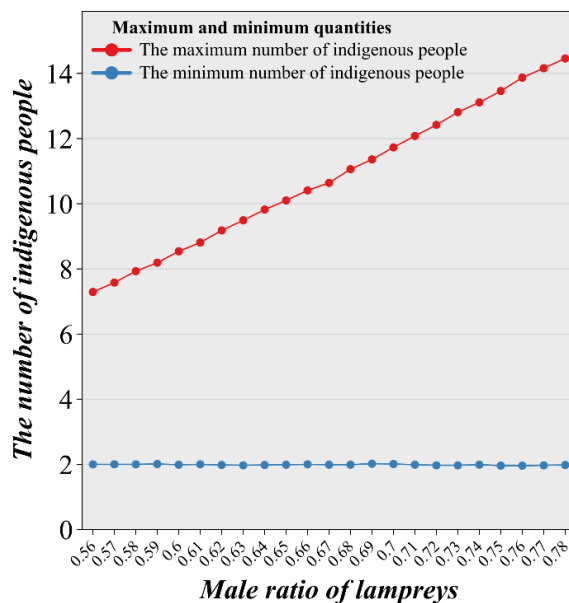


Figure 4 Changes in the number of indigenous peoples

The following conclusions can be drawn from the above research:

1. Within the male ratio range of 0.56 to 0.78, the maximum number of indigenous people increases almost linearly with it, indicating that an increase in the male ratio of lampreys within a certain range has a positive trend toward predators in the ecosystem.
2. The minimum number of indigenous people has hardly changed, and overall, it is relatively stable.

3.4. Lampreys, natural enemies, and food

3.4.1 Modeling process

This study placed lampreys in the middle of the food chain, divided into three trophic levels. The first and third are small and large fish species, respectively, and simulated using the Lotka-Volterra model.

3.4.2 Programming results

This work found that the changes in the proportion from 0.56 to 0.78 were not significant for the three nutrient levels, so as shown in Figure 5 this work selected the image with a male proportion of 0.60 as a representative.

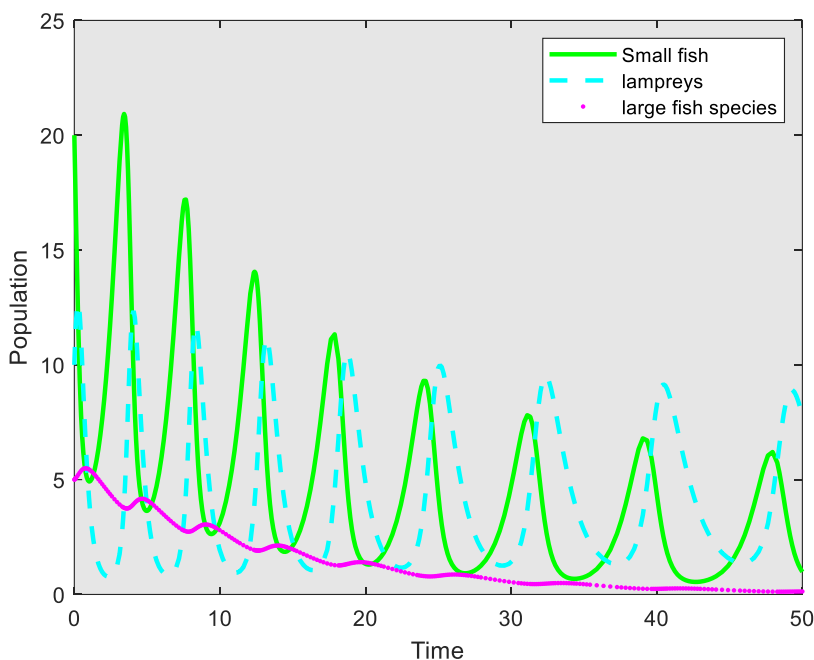


Figure 5 An ecosystem model with a male proportion of 0.60

The following conclusions can be drawn from the above work:

1. The changes in the three nutrient levels are not particularly significant compared to the two levels, possibly due to a more complex food chain and better ecosystem stability.
2. Large fish species tend to become extinct over a long period, leaving only lampreys and small fish to grow and fall, and their numbers fluctuate periodically.
3. From a long-term perspective, the population of lampreys will dominate, indicating their strong survival ability in the ecosystem.

4. Conclusions

First of all, this work briefly described the influence of age and water temperature on the male-to-female ratio of lampreys and visualized the impact of different ages on the sex ratio and the optimal survival water temperature for lampreys through relevant data. Almost at any age group, the number of males is almost greater than females, and at 38.166 degrees, the lamprey's total catch reached its maximum. In the second place, to clarify the impact of the sex ratio of lampreys on ecosystems, this

study applied the Lotka-Volterra model and differential equations and then assumed two models corresponding to the food chains of two lampreys. By observing changes in the number of other species in the ecosystem, we explored the impact of the sex ratio of lampreys on the ecosystem. The results showed that in shorter food chains, the maximum number of predators increased with the increase of male proportion in lampreys, while in longer food chains, the maximum number of predators and food in lampreys changed less.

This study reveals the application of a research approach and framework in the field of ecology which can help to solve the number of mutual constraints between different nutritional levels in the food chain.

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