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Dynamic Modeling of Lamprey Population and Gender Structure Evolution

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Abstract

The gender ratio of lamprey can vary with environmental resource conditions. We have developed a dynamic model that considers the population dynamics and gender structure evolution of lamprey. By incorporating the gender ratio of lamprey and resource availability, we simulated the dynamic evolution process under different parameters based on real data. we established a relationship model between the population dynamics, gender ratio, and environmental resource interactions, based on the Lotka-Volterra equations. The results showed that while the gender structure of lamprey improves its adaptability, an increase in the male ratio can also increase mating competition, potentially accelerating population growth. However, when the male ratio becomes too high, excessive mating competition can lead to decreased survival rates, resulting in population fluctuations or decline.

Keywords

Dynamic Modeling; Lamprey Population; Gender Structure Evolution; Environmental Factors; Ecological Dynamics.

1. INTRODUCTION

Most animal species are typically classified into male or female, but there are also some species that exhibit adaptive sex ratio variation. The lamprey is one such species, characterized by its unique appearance and physiological features, making it a species of great interest. Their bodies are elongated and snake-like, usually measuring around 60-100 centimeters in length, with some individuals reaching up to 1 meter. One of the distinguishing characteristics of lamprey is the presence of seven pairs of gill slits, which is also the origin of their name [1].

They play different roles in different habitats, being parasitic in some areas, causing significant impacts on the ecosystem, while serving as a food source in other regions, such as among indigenous populations in Scandinavia, the Baltic Sea, and the northwestern Pacific Ocean. The sex ratio of lamprey is influenced by external environmental factors, the growth rate during the larval stage, and food availability, which determine the gender. In environments with limited food supply, the male ratio is higher, approximately 78%, whereas in environments with more abundant food, the male ratio is around 56%.

2. RELATED WORK

In exploring the dynamic interactions between environmental conditions, sex ratios and population dynamics in ecosystems, lampreys make for a fascinating case study due to their adaptive changes in sex ratios and significant ecological impacts. Characterised by an elongated, snake-like body with seven pairs of conspicuous gill slits, lampreys play a variety of roles in different habitats - from parasitic entities affecting host species, to important food sources for

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indigenous populations in regions such as Scandinavia, the Baltic Sea and the Pacific Northwest [2]. Their sex ratios are influenced by environmental factors such as food availability and larval growth rates, highlighting a complex adaptive strategy: a higher proportion of males when food is scarce and a more balanced proportion of males when resources are abundant.

To dissect these dynamics, we developed a dynamic model based on the fundamentals of the Lotka-Volterra equation that combines population dynamics with the evolution of sex structure in response to fluctuations in environmental resources. Based on rigorous empirical data, the model simulates the interactions between lamprey populations and their environment, revealing how sex ratio adjustment acts as an ecological adaptive mechanism. Specifically, it elucidates how an increase in the proportion of males may initially promote mating competition and population growth, but that excessive male dominance may subsequently lead to a strain on survival due to increased competition, which may destabilise the population size [3].

Our modelling work extends to the wider ecological context by considering the effects of seasonal resource variability - from resource abundance in spring to promote growth, to resource scarcity in winter to challenge survival - on lamprey populations, and by extension, the effects of predator-prey dynamics in their ecosystems. Through this lens, we observe that the effects of lamprey depletion rates and sex ratios on fecundity play a key role in regulating the long-term balance of populations and resources.

By employing a range of parameters based on real-world data and literature, such as optimal birth rates, daily growth rates reflecting environmental carrying capacity, and population density-based adjustments to depletion rates, we were able to predict changes in lamprey population size, resource availability, and sex ratio over time. These predictions highlight cyclical fluctuations in population size, with initial growth leading to resource depletion, followed by stabilisation at lower levels of resource abundance and an eventual increase in the proportion of males [4].

Our findings emphasise the delicate balance within ecosystems, where the sex structure of a species such as the lamprey not only affects its own population dynamics, but also has cascading effects on wider ecological interactions and resource distribution. This highlights the need to consider sex ratios and environmental resources in ecological modelling and conservation strategies to better understand and predict the dynamic response of ecosystems to changing conditions.

3. ECOLOGICAL SYSTEM DYNAMIC MODELS

In the field of ecological dynamics, fluctuations in lamprey sex ratios under the influence of external environmental determinants are a key factor in regulating population structure and abundance. This phenomenon is particularly important when considering the subtle role of female dominance in certain environments, as it has the potential to catalyse increases in population size [5]. Such demographic changes can significantly affect competition and resource allocation among species, thus creating a ripple effect throughout the ecological spectrum. The intricate relationship between sex ratios and reproductive potential further complicates this dynamic as it is closely linked to birth rates and the feasibility of effective female pairing, thus having far-reaching effects on food chain dynamics and overall ecological balance.

To gain a deeper understanding of these interactions, our study developed an advanced model of ecosystem dynamics. The model was carefully constructed based on an extensive review of the literature and is able to accurately simulate the complex interactions between lamprey populations and the surrounding ecosystem under various sex ratio differences [6]. By integrating the multifaceted effects of sex ratio fluctuations on reproductive strategies and subsequent population outcomes, the model demonstrates the sophistication and reliability of

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current ecological modelling efforts. It not only contributes to a deeper understanding of dynamic processes in lamprey populations, but also provides valuable insights into the broader effects of sex ratio adjustments in ecosystems. Enhanced academic discussions emphasised the need to incorporate sex ratio factors into ecological dynamics analyses, highlighting its critical role in shaping population structure and guiding ecosystem management strategies.

4. MODEL ESTABLISHMENT

The population growth rate is not only determined by the overall birth rate, but also by the proportion of females and the population's survival rate. If the proportion of females increases, each male may have more mating opportunities, thereby increasing the population's birth rate. Conversely, if the proportion of females decreases, it may limit the population's reproductive capacity and birth rate [7]. The temporal variation in population size is illustrated in Figure 1.

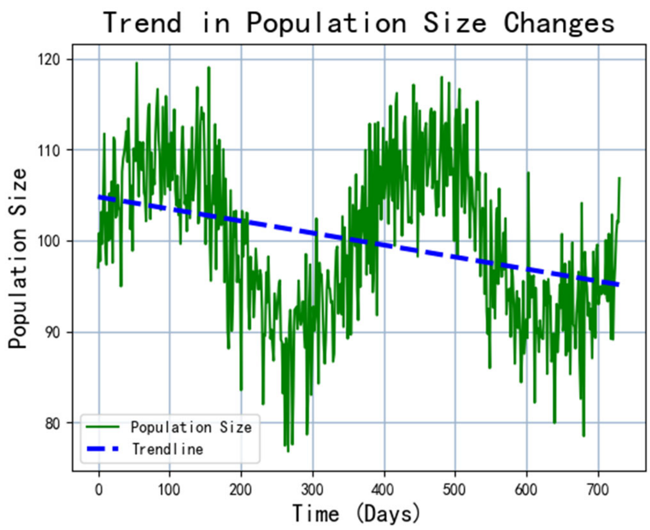

Figure 1. The trend of population size over time

The quantity of births at a specific moment can be represented as:

$$x_1 = A \cdot (1 - W_{male}(t)) \cdot S(Q(t), E(t)) \cdot Q(t)$$

The quantity of deaths at a specific moment can be represented as:

$$x_2 = D(Q(t), E(t)) \cdot Q(t)$$

In this case, $D(N(t), R(t))$ represents the mortality rate function, which depends on the population size and resource availability.

Thus, we can obtain the population growth rate from this:

$$\frac{dQ}{dt} = A \cdot (1 - W_{male}(t)) \cdot Y(Q(t), E(t)) \cdot Q(t) - D(Q(t), E(t)) \cdot Q(t)$$

The average resource quantity for each season in a year, as depicted in Figure 2, can be derived from actual natural data.

Spring: Resources are relatively abundant, promoting plant growth and reproduction, providing pollen and nectar as a food source.

Summer: Resources are relatively scarce, with high temperatures and drought conditions causing some plants to enter dormancy or reduce growth [8].

Autumn: Resources gradually become abundant as plants bear fruit and disperse seeds. Animals prepare for hibernation or migration, acquiring more food reserves.

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Winter: Resources are relatively scarce, with plants entering dormancy and animals relying on stored food or other strategies to survive the winter.

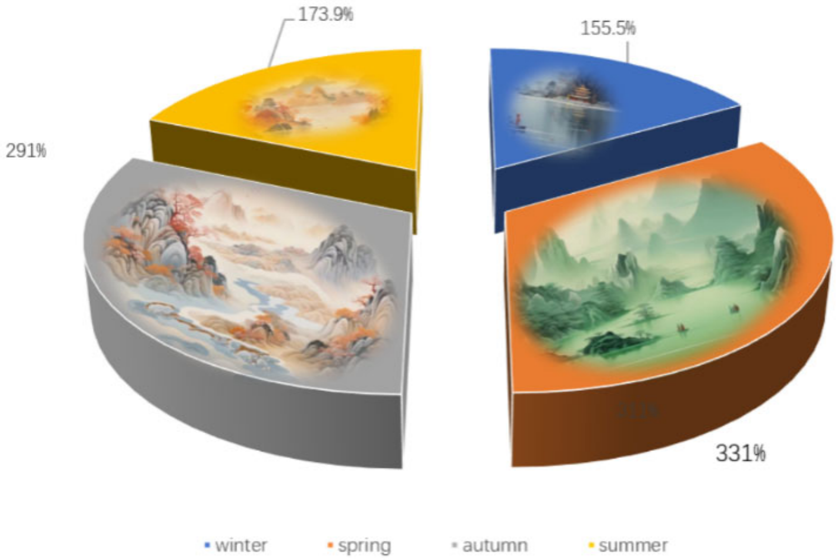

Figure 2. Proportion of average resource quantity for each season

Different species utilize resources in different amounts and ways within an ecosystem. When resources are abundant, population growth is typically constrained, possibly due to increased competition for the same resources, thereby limiting individual population growth. Conversely, when resources are scarce, population size usually decreases. Resource scarcity leads to difficulties in predation, competition, and reproduction, resulting in reduced individual survival and reproductive success rates, ultimately leading to a decline in population size [9]. We employed a scatter plot to depict the relationship between population size and resource abundance, as shown in Figure 3.

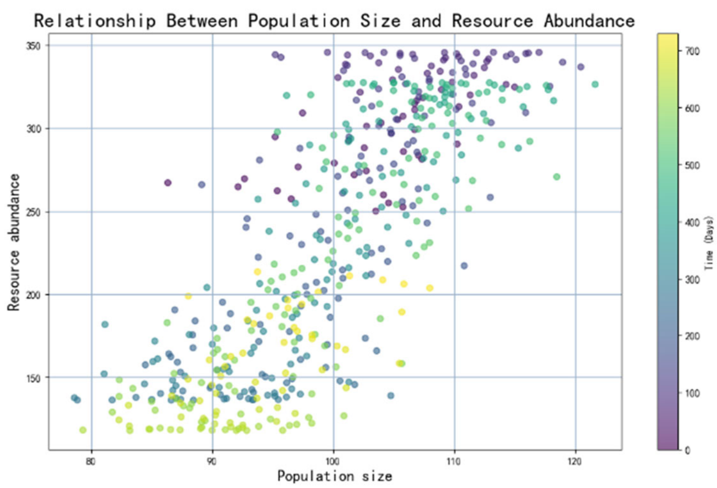

Figure 3. The relationship between population size and resource abundance

The relationship between predator population and resource abundance in different seasons is referred to as predator-resource interaction in ecology. This interaction is a vital component of predator-prey food chains. The relationship between predator population and resource abundance in different seasons is depicted in Figure 4.

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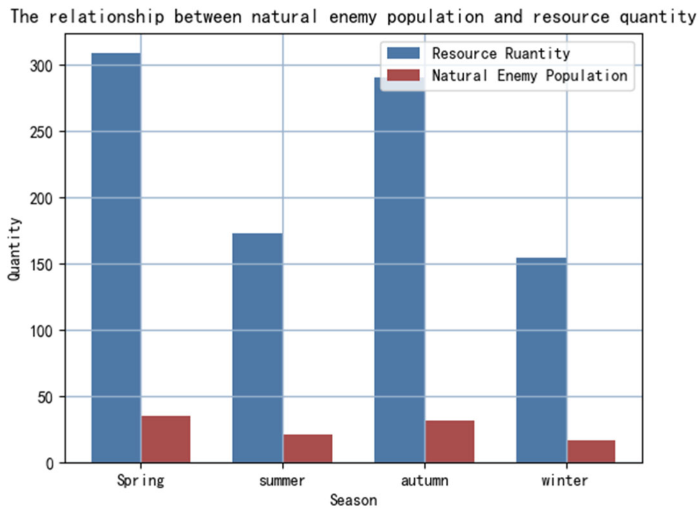

Figure 4. The relationship between predator population and resource abundance

In different seasons, changes in resource abundance can affect the quantity of predator populations. Generally, an increase in resource abundance leads to an increase in predator population, while a decrease in resource abundance results in a decrease in predator population. This is because predators obtain energy and nutrients by preying on resources, and changes in resource abundance directly impact their survival and reproduction.

Specifically, during seasons of abundant resources, the population of resource species increases, providing more food sources for predators, resulting in an increase in predator population. Conversely, during seasons of scarce resources, a decrease in the quantity of resources can lead to insufficient food supply for predators, potentially causing a decline in predator population.

However, the relationship between predators and resources is also influenced by other factors, such as adaptability and competition. Furthermore, the interaction between predators and resources can be complex and dynamic, potentially influenced by factors such as seasonal changes, climate conditions, and environmental pressures [10].

The changes in resources are influenced by both natural growth and the consumption by lampreys. This can be expressed as：

$$\frac{dE}{dt} = R(E(t)) - C(Q(t)) \cdot Q(t)$$

In this context, $C(Q(t))$ represents the per capita consumption rate of resources, which can vary with changes in population density.

We consider the variation in gender ratio as a result of multiple biological and environmental factors, such as temperature, food availability, etc. We denote these factors as function $T(Q(t), E(t))$.

Based on the model and substitution, we have:

$$\frac{dW_{male}}{dt} = T(Q(t), E(t)) \cdot (1 - W_{male}(t)) - R(Q(t), E(t)) \cdot W_{male}(t)$$

Here, T and R represent the factors that cause a skew towards males or females in the gender ratio.

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5. CONCLUSION

After establishing the model, referring to the existing literature, we assume the following parameters:

Based on actual data, we estimate the birth rate by fitting the model and find that 0.1 is the optimal value.

Since the lamprey population is relatively small, we can assume that its daily growth rate is 0.05. As the quantity of resources gradually approaches the environmental carrying capacity, there is a characteristic slowdown in growth rate. Therefore, we set the environmental growth rate at 550 to limit the speed of resource growth. Lampreys may have a lower consumption of resources or require fewer resources in their lifestyle, so we set the basic consumption rate at 0.02.

Since lampreys have a greater ability to acquire resources, or the environment provides relatively abundant resources, the impact of competition for resources among individuals on resource consumption is small. Therefore, we set the consumption rate adjustment coefficient that changes with population size at 0.00005.

Resources are key elements necessary for biological growth, reproduction, and maintenance of physiological functions. The scarcity or insufficiency of resources can significantly affect the survival and survival rate of biological individuals. The increase (or decrease) in unit resources has a significant impact on biological survival, so it is necessary to set a larger coefficient at 0.01. The competition for resources among lamprey individuals is not intense, and the environmental conditions are relatively relaxed. The impact of population density on viability is small, so the coefficient for the impact of population density on survival rate is set at 0.005. For the same reason, we can also set the basic mortality rate at 0.05, the coefficient for the impact of population density on mortality rate at 0.0001, and the coefficient for the impact of resource quantity on mortality rate at 0.0001. By solving it, we can obtain the change curves of lamprey population size, resource quantity, and male ratio over time, as shown in Figure 5.

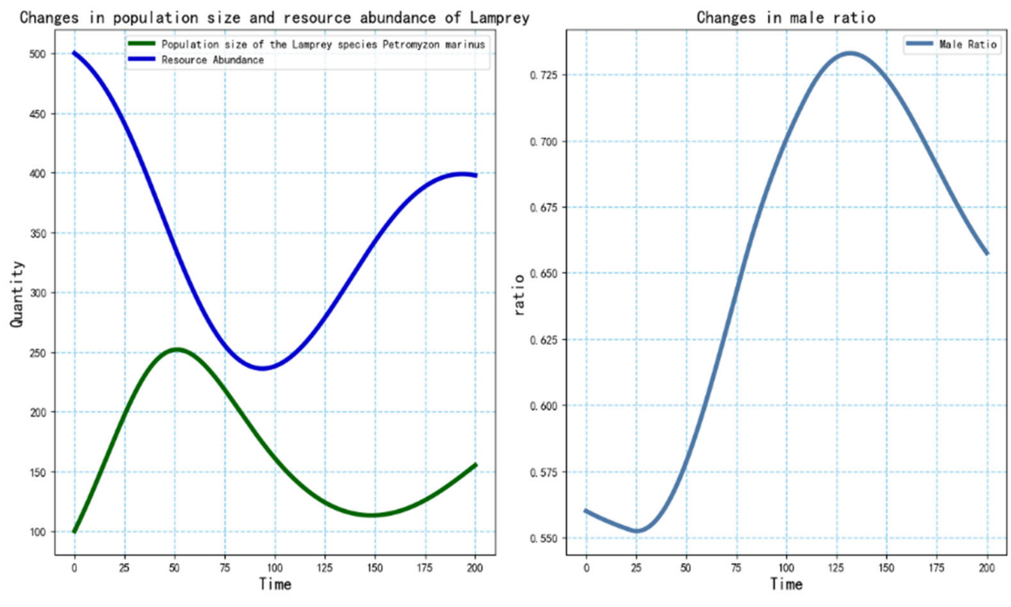

Figure 5. Comparative graph of changes in lamprey population size, resource variation, and male ratio

From Figure 5, it can be observed that over time, the population number (i.e., the number of lampreys) shows a certain periodic fluctuation, which is the result of the interaction between population growth and mortality factors. The population number tends to grow in the initial

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phase and then gradually stabilizes. The resource level reaches a higher level at the beginning and gradually decreases with the increase in population number. The consumption of resources is positively correlated with the population size. The resource level will gradually decline and eventually stabilize at a lower level. The male ratio (i.e., the proportion of male lampreys) is lower in the initial period and gradually increases over time. When the resource level is low, the male ratio will gradually increase until it reaches a higher stable level.

The changes in the gender ratio of lampreys can have the following impacts on the larger ecosystem: When the male ratio increases, mating competition will also increase, which may accelerate population growth. However, when the male ratio is too high, mating competition may become excessively intense, leading to a decrease in individual survival rates, thereby causing fluctuations or declines in population numbers. Conversely, when the male ratio decreases, mating competition diminishes, and individual survival rates may improve, but the speed of population growth may slow down. In situations where resources are relatively abundant, reduced competition among individuals may not have a significant impact on population numbers, allowing the population to remain relatively stable.

6. DISCUSSION

Dynamic modelling of the evolution of population and sex structure in lampreys is at the forefront of ecological research, revealing the complex mechanisms by which environmental factors shape biological communities. Our study of lamprey ecology utilises a complex dynamic model that provides insights into the adaptive strategies of this unique species, particularly in response to fluctuations in environmental resources. The model is based on the fundamental Lotka-Volterra equation and is carefully calibrated to empirical data to simulate the delicate interactions between lamprey populations, their sex ratios and the ecosystems they inhabit.

Central to our findings is the recognition that changes in sex ratios due to external environmental conditions have a significant impact on lamprey population dynamics. This effect is multifaceted, affecting not only the fecundity and potential growth rate of lamprey populations, but also the competitive dynamics and resource use in their ecosystems. Specifically, the model reveals how shifts in female dominance under specific conditions catalyse increases in population size, which in turn puts pressure on resource availability and species interactions in the ecosystem.

In addition, our analyses provide insights into seasonal shifts in resource availability and their effects on lamprey populations and ecosystem health. By incorporating seasonal resource fluctuations into our modelling, we reveal complex interdependencies between resource abundance, sex ratio changes and their collective impact on ecological balance. This approach allows us to predict and analyse cyclical patterns of population growth, resource depletion and sex ratio over time, leading to a comprehensive understanding of lamprey ecology and its broader ecological impacts.

This study ultimately provides a nuanced understanding of the delicate balance within ecosystems in which lamprey sex ratios, influenced and shaped by environmental resources, play a pivotal role in ecosystem dynamics. It highlights the need to incorporate sex ratio changes and environmental resource dynamics into ecological modelling and conservation strategies. This study not only improves our understanding of lamprey populations, but also enriches the ecological discourse by emphasising the importance of the evolution of sex structure in the study of population dynamics, providing valuable perspectives for future research and ecosystem management.

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