The Impact of Sex Ratio Adjustment on Population Dynamics and Ecosystems in Marine Sea Lampreys

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Abstract. As climate change leads to more frequent intense environmental changes in aquatic ecosystems, understanding how marine species adapt under changing conditions is increasingly important. This study investigated the survival strategies of sea lampreys under varying temperatures and food availability. A logistic model was developed based on changes in sex structure to examine if sex ratio adjustment could act as an adaptive mechanism under different environments. A food chain Lotka-Volterra model then investigated the impacts of sex ratio changes in sea lampreys on ecosystem dynamics. Resource utilization ratio varied with sex ratios, maximizing at 37.16% and minimizing at 1.43. Excessive sex ratio changes could destabilize the ecosystem. A population dynamics model compared the effects of initial fixation and variable sex ratios on population size. Sea lampreys showed the highest predation rate at a sex ratio of 1.43, best suited for population growth, averaging 35.31%, much higher than 4.68% under initial fixation. Findings provide insights into how species use plasticity to adapt to global change and may inform sea lamprey control strategies.

Keywords: Logistic model, Lotka-Volterra model, sex ratio, Ecosystems.

1. Introduction

Understanding the dynamics of species adaptation and survival in the face of escalating environmental challenges is becoming increasingly important. Among the myriad species affected by these changes, some have shown compelling resilience and adaptability through changes in sex ratios sea lamprey, such as the sea lamprey[1].

A logistic model describing the population dynamics of the sea lamprey was first constructed to analyze the effect of sex ratio on its growth. Logistics is a machine learning algorithm widely used in classification problems and was first proposed by David Cox in 1958[2]. The algorithm can effectively model binary classification problems and can be used to predict probabilistic outputs. In ecological research, logistic regression is often used to analyze species distribution, population dynamics, and other problems[3]. In this study, we used a logistic regression model to analyze the relationship between population size change and sex ratio of sea lamprey. By constructing the logistic regression model, we could quantify the influence of the change in sex ratio on the population size due to environmental impacts, and provide a basis for further studies on the population dynamics of the sea lamprey. In addition, we combined the logistic regression model with the Lotka-Volterra food chain model to develop an ecosystem model that included sex ratio as a factor, which is a classical interspecific competition model, and we extended it to analyze the relationship of the food chain. We extended the Lotka-Volterra model, a classic interspecific competition model, to analyze the relationships in the food chain. This approach allowed us to analyze more comprehensively the effects of the sea lamprey's position in the food chain and its sex ratio on the whole ecosystem.

In general, the logistic regression algorithm and the Lotka-Volterra food chain model are mature and reliable methods that have been widely used in ecological modeling and population dynamics analysis. However, existing studies have mainly focused on the population dynamics and resource utilization of sea lampreys[4-7] or the mechanisms of changes in sex ratios of sea lampreys due to external influences[8], but lacked an in-depth analysis of their roles and impacts on the whole ecosystem. In the present study, we successfully applied it to the analysis of sea lamprey population changes and combined it with other models to systematically analyze the effects of sea lamprey sex ratio changes on the whole ecosystem and assess its potential benefits to other species by constructing a more complex mathematical model, to fill the gaps in previous studies.

2. Sex Ratio and Ecology in Marine Sea Lampreys

2.1. Data collection and pre-processing

To ensure the accuracy and usability of our data, we selected some biological data published by the Royal Society on juvenile sea lampreys sampled in natural streams in Michigan and Quebec, Canada[9].

First, we screened the data and removed outliers using the interquartile test. After screening, we found one outlier in sea lampreys' weight(*W*) and two outliers in length(*len*).

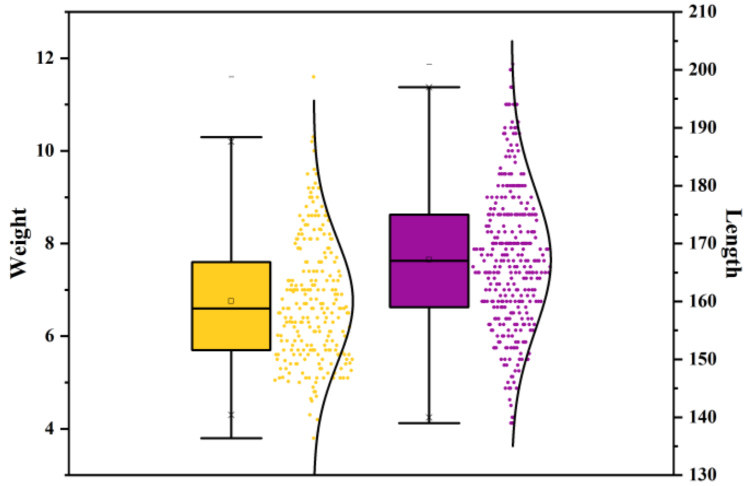


Figure 1: Sample data on length and weight of sea lampreys

Secondly, it can also be seen from Figure 1 that the length and weight of the sea lamprey were normalized to the present. We also used SPSS software to test the length, weight, and temperature data for normal distribution, as shown in Table 1. We found that the significance of both the chi-square test and the Shapiro-Wilk test (W-test) was greater than 0.05, so the null hypothesis was rejected and the sample was considered to meet the requirements of a normal distribution. Therefore, the sample data can be used in the logistic regression model proposed below.

Table 1: Normality test

	chi-square test	Shapiro-Wilk test
Len	0.2	0.886
W	0.2	0.225

Finally, because there were missing values in the length and weight of sea lampreys, we filled in the missing values with the average of the two neighboring data.

2.2. Growth modeling of sea lampreys in response to changes in sex ratio

In this section, only the change in the sex ratio of the sea lampreys population was modeled for analysis. In this case, there is only one population in a given area. According to the research on the sex ratio of sea lampreys, environmental conditions affect the growth rate of the sea lampreys and the growth rate affects its sex ratio[10], so we propose the following steps:

Step 1: We first establish the growth model of sea lampreys. Here we use two variables to respond to the growth change of sea lampreys, which will increase according to the Logistic model. We have

$$\frac{dlen}{dt} = r_{len}(1 - \frac{1en}{len_{\max}}) \times len \tag{1}$$

$$\frac{dW}{dt} = r_W(1 - \frac{W}{W_{\max}}) \times W \tag{2}$$

Where r_{len} is the inherent rate of change of length and r_W is the inherent rate of change of weight.

Step 2: Since the growth rate of sea lampreys is different in different environments, that is to say, the environmental conditions affect the growth rate of sea lampreys, we must modify the logistic model based on the logistic model according to the characteristics of the external environment such as food supply and temperature(T). ε is the scale factor for the impact of food while σ is the scale factor for the effect of temperature. The growth model of sea lampreys can be expressed as

$$\frac{dlen}{dt} = r_{len}(1 - \frac{1en}{len_{\max}} - \sigma T - \varepsilon) \times len \tag{3}$$

$$\frac{dW}{dt} = r_W(1 - \frac{W}{W_{\max}} - \sigma T - \varepsilon) \times W \tag{4}$$

The length and weight variation curve is shown in Figure 2.

Step 3: Based on the above differential equations, the final model can be obtained by synthesizing the test.

$$len = \frac{len_{\max} \times (\varepsilon + \sigma T - 1)}{e^{\{\frac{\ln\left[\frac{len_{\max} \times (\varepsilon + \sigma T - 1)}{50} + 1\right]}{\varepsilon + \sigma T - 1} + r_{len} \times t\} \times (\varepsilon + \sigma T - 1)} - 1} \tag{5}$$

$$W = \frac{W_{\max} \times (\varepsilon + \sigma T - 1)}{e^{\{\frac{\ln\left[\frac{W_{\max} \times (\varepsilon + \sigma T - 1)}{W_0} + 1\right]}{\varepsilon + \sigma T - 1} + r_W \times t\} \times (\varepsilon + \sigma T - 1)} - 1} \tag{6}$$

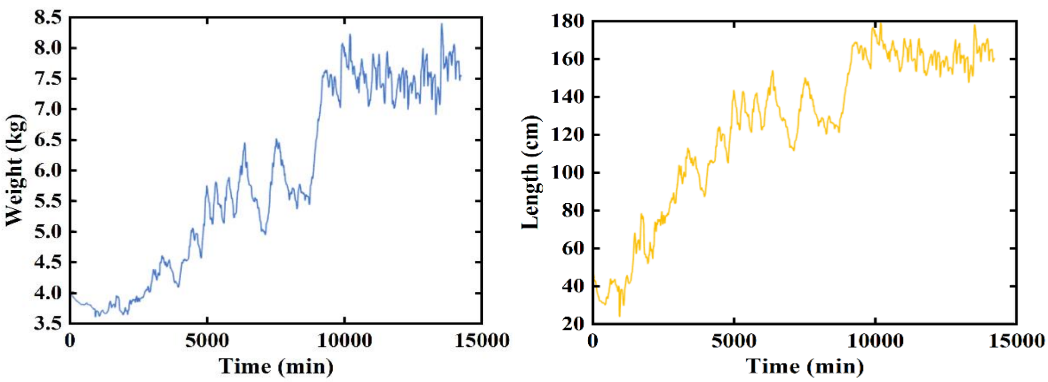


Figure 2: The changes in length and weight over time.

2.3. Modeling of interspecific interactions based on the sex ratio model

Interaction between species is the basis for the formation of biota. Based on the relationship between species, interactions can be categorized into reciprocity and competition. For the sea lampreys in this model, since its most important natural enemy is humans we have assumed that anthropogenic mortality is included within the mortality rate. Therefore, the sea lampreys are considered to be at the top of the food chain and we only consider competitive relationships towards prey.

The Lotka-Volterra model is a classic model of interspecific competition based on a logistic model. We extended this model to create a food chain model of species competition based on sex.

$$\frac{dN_m}{dt} = r_m \times N_m - p_{fm} \times N_f - \alpha \times N_m + a \times N_m \times P \tag{7}$$

$$\frac{dN_f}{dt} = r_f \times N_f - p_{mf} \times N_m - \beta \times N_f + b \times N_f \times P \tag{8}$$

where *a*, and *b* represent the predation proportion factor of male and female sea lampreys, respectively, α β and denote the mortality rate, and $p_{fm,}$ p_{mf} are the predation rates between males and females, respectively. The value of the gender ratio is represented by *R(t)* at time *t*. $N_m(t)$, and $N_f(t)$ represent the mean number of males and the mean number of females in the population, respectively, and the sum is the total population size.

The growth rate affects the sex ratio, so the model of sex ratio change is considered

$$\delta = R(t+1) - R(t) = \frac{N_m(t+1)}{N_f(t+1)} - \frac{N_m(t)}{N_f(t)} = \frac{N_m(t) \times (r_m + 1)}{N_f(t) \times (r_f + 1)} - \frac{N_m(t)}{N_f(t)} \tag{9}$$

And, we consider that the predation efficiency of the sea lampreys is related to the number of males and females as follows

$$\frac{dp}{dt} = r_p \times p - a \times N_m \times P - b \times N_f \times P \tag{10}$$

Therefore, taking this into account we derived images of the change in sex ratio and predation efficiency of the sea lampreys in the food chain over time in the absence of interference from extraneous factors. For sea lampreys *a*, *b*, $p_{fm,}$ p_{mf} and so on the values are shown in Table 2. Specific data can be obtained through field surveys or based on the literature, and the following data are only used to show how our model can be applied.

Table 2: Relevant parameters

a	b	α	β	p_{fm}	p_{mf}	r_m	r_f	r_p
0.002	0.001	0.02	0.02	0.0001	0.0002	0.04	0.03	0.1

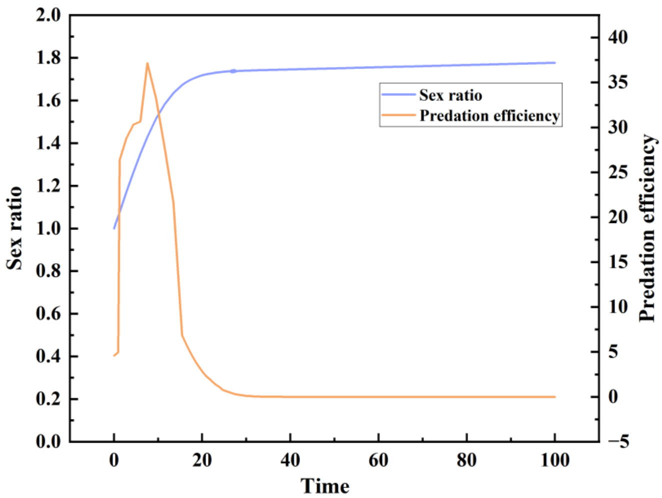


Figure 3: Images of changes in sex ratios and predation efficiency in the food chain of the sea lampreys

From Figure 3, it can be concluded that as time passes, the sex ratio increases rapidly in the initial 20 days, and then increases slowly, but has been showing an increasing trend. Predation efficiency showed a trend of increasing and then decreasing, with a maximum value of 37.16%, which corresponds to a sex ratio of 1.43. This suggests that if there is no interference from extraneous factors, the sea lampreys will hunt their prey indefinitely, which leads to a significant reduction in the biomass of its prey, and food begins to be scarce. To adapt to the limited resources, the number of sea lampreys males will increase, and the predation efficiency will be improved through the regulation mode of getting a larger sex ratio. However, due to unlimited prey, after a while, even further changes in the sex ratio of sea lampreys cannot make predation more efficient and resource availability decreases. Therefore, sea lampreys are subject to constraints in the food chain, such as spatial capacity and natural conditions, etc., so that their sex ratio can be adjusted within a certain range to maximize their predation efficiency, which makes full use of the resources and does not lead to the extinction of their prey and maintains the balance and stability of the ecological environment.

3. Results

In recent years, many scholars have studied the relationship between the sex ratio and population dynamics of the lampreys [4,5]. They found that adaptive changes in the sex ratio can enhance the adaptability of the population when the environment changes. The sex ratio of sea lampreys varies with food sufficiency. In times of food scarcity, the proportion of females increases to ensure the continuation of the population. In biology, sex ratio is a key factor that affects the reproduction and viability of a population. This paper aims to investigate the effects of changes in the sex ratio on population stability and resource use efficiency.

In this section, we first hypothesize that the adaptations of the sea lampreys do not change in response to environmental changes, and then we compare the changes in population size under food-sufficient versus food-poor conditions. Next, we observe the fluctuation of population size when the sex ratio changes. By comparing the two, we initially analyze the relative advantages and disadvantages of the change in sex ratio.

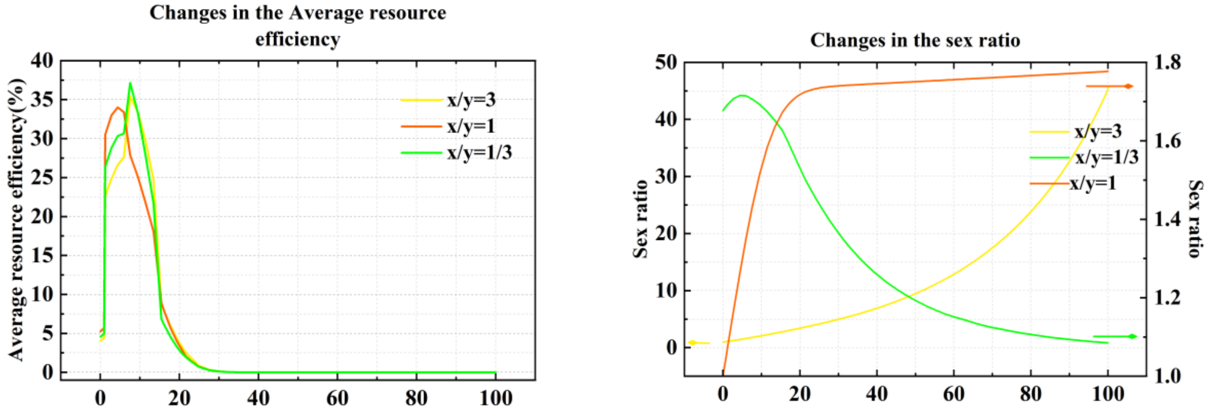
To facilitate the study, we defined two scaling factors x, y to quantify the fixation adaptivity of the sea lampreys, and investigated the interaction equations (7)(8) when the fixation ratio was $x:y=1:1,\ 1;2$ and 2:1, respectively, which r_m and r_f changed from the original variation subject to the food supply to a fixed value *r*.

$$\frac{dN_m}{dt}=\frac{xr}{x+y}\times N_m-p_{fm}\times N_f-\alpha\times N_m+a\times N_m\times P \tag{11}$$

$$\frac{dN_f}{dt}=\frac{yr}{x+y}\times N_f-p_{mf}\times N_m-\beta\times N_f+b\times N_f\times P \tag{12}$$

$$\frac{dP}{dt}=r_p\times P-a\times N_m\times P-b\times N_f\times P \tag{13}$$

To assess resource use efficiency, we focused on the ratio of prey number to total food quantity. In addition, populations with a change in sex ratio showed a higher ratio of predation number to total food quantity in resource utilization efficiency, as shown in Figure 4, where only a change in sex ratio resulted in a higher resource utilization efficiency compared to the initial fixed adaptive ratio. The highest value of resource utilization efficiency averaged 35.31%, which is much higher than the average resource utilization efficiency of 4.68% for the initial fixed adaptive ratio. However, changes in sex ratios do not often bring benefits. As shown in the figure, resource utilization efficiency tended to decrease again after some time. Excessive numbers of males in the sea lampreys may also pose a threat to other species, leading to a decrease in species richness. Therefore, when assessing the contribution of the lampreys to ecosystem stability, a combination of its population size and its impact on other species needs to be considered.



(a) (b)

Figure 4: (a) Changes in population resource utilization under three adaptive ratios

(b) Changes in sex ratio over time under three adaptive ratios

In summary, changes in the sex ratio have significant effects in terms of population stability and resource utilization efficiency. This provides a new perspective on biodiversity conservation and ecological balance. In the future, the adaptive mechanisms of sex ratio changes in different organisms and their broader impacts on ecosystems should be further explored.

4. Conclusions

In summary, we successfully investigated the effects of sex ratio changes on the resource utilization of marine sea lampreys by building a population dynamics model of the lamprey. We constructed a logistic model of population changes of marine sea lampreys and analyzed the effects of sex ratio on their populations. Then, we constructed a Lotka-Volterra model to study the relationship between sea lampreys in the food chain and the external environment and modeled the ecosystem based on changes in sex ratio caused by environmental changes. When the sex ratio of the sea lamprey changed, its resource utilization ratio also changed, with a maximum resource utilization ratio of 37.16% and a minimum sex ratio of 1.43. This indicated that excessive changes in the sex ratio could unbalance the ecosystem. Based on the interaction equation and setting the environmental adaptation value as a constant as a correction, we developed a population dynamics model for the sea lamprey and compared the effects of two scenarios, the initial fixed condition and the change of sex ratio, on the population size. We found that sea lamprey had the highest predation rate at a sex ratio of 1.43, which was most suitable for population growth, and the highest predation rate averaged 35.31%, much higher than the average predation rate of 4.68% at the initial fixed acclimation ratio. This paper provides a research idea and framework for solving the problem between resource fitness and sex ratio, which also provides a new strategy for Lotka-Volterra modeling for adjusting the sex ratio of species in the field of marine ecology.

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