Predicting the sea lamprey population dynamic and ecosystem stability based on sex ratio corrected logistic model

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Abstract. The sex ratio of the sea lamprey(*Petromyzon marinus*) is influenced by population density. A sex ratio corrected population model and a ecosystem stability model were established based on the logistic population model. In these models, the population growth rate (r) is corrected by sex ratio, and the deviation degree from environment carrying capacity (K) at different sex ratio scenarios is quantified. Using the models, the population dynamic and its effect on the ecosystem stability are simulated. The male dominant lamprey populations exhibit decreasing trends. The stability of the ecosystem decreases with the increase of male ratio.

Keywords: Sea lampreys, sex ratio, logistic model, population dynamic, ecosystem stability.

1. Introduction

The Sea lamprey (*Petromyzon marinus*) is a jawless cartilaginous fish. This species spends the early stages of their life in streams and rivers, and the middle stage of their life in the ocean or in a large freshwater lake. The larval lamprey hatch from eggs and drift river downstream with the current. When they locate suitable habitat, they burrow in and take up residence, filter-feeding on algae, detritus and materials [1]. Once the larval transformation is complete, the sea lampreys begin the next life stage as a parasite of fish: the juvenile sea lampreys move into deeper water and begin to seek host fish on which to feed over the course of 12-20 months. Juvenile sea lampreys have been observed to have fed on most fish species in the Great Lakes[2,3]. Therefore, predicting the population size of lampreys and its impact on other species in the ecosystem is of great significance for managing fishery resources.

It has been suggested that sex differentiation of the sea lamprey in the Great Lakes is influenced by population density[4], with high-density populations being more likely to be male-biased than low-density populations. In the larval stage, nutrition levels in larval habitat may influence sex assignment in this species, with larvae that consume more nutrients being more likely to develop as female[5]. High relative number of males being almost associated with larger spawning populations [5]. In the juvenile stage, as sea lamprey abundance increased, there were coincident declines in host abundance[6]. Female mortality rates during the juvenile stage may have increased as host abundance decreased, due to higher energetic costs associated with the maturation of ovaries[7]. At the low abundance of host, males became the predominant sex in the sea lamprey population, then the reproductive rate of the population decrease and the lamprey population decrease. Following this decrease, the hosts became more abundant, sea lamprey females increase and population increase. Therefore, the population growth rate of sea lamprey is not only influenced by environment carrying capacity, but also by the sex ratio of the population.

Although many studies have analyzed the relationship between population density and sex ratio using long term fishing capture data [8, 9], a model being used to predict the sea lamprey population corrected by sex ratio is still lack. It is necessary to establish mathematic models incorporating sex ratio in order to predicting the sea lamprey population dynamic and its effect on the stability of the ecosystem. The logistic growth model is a self-limiting population-growth model[10], using census data to quantify the net effect of population size N on the per capita rate of exponential population changer [11]. When the sex ratio is considered, the effect of the N increase on r is influenced by the sex ratio. The effect of N on r could decrease in the male dominant population. Thus, the r should be

corrected by sex ratio in the sea lamprey population model. The environment carrying capacity K is the upper population limitation that the ecosystem can maintain the stable status, thus the capacity of a population maintaining K can reflect the stability of the ecosystem. Therefore, a model to predicting the effect of Sea lamprey population on ecosystem stability could be established based on the logistic model to evaluate the deviation degree from K under different sex ratio scenarios.

In this article, a sex ratio corrected population growth logistic model and a logistic model-based ecosystem stability evaluating model were established, and the population dynamic and its effect on the ecosystem stability under different sex ratio scenarios were simulated using the two models. The models will be benefit for the sea lamprey population control.

2. Sex ratio corrected population model establishment

2.1. The Logestic model

It is assumed that the population of lampreys in a certain habitat is N, and the growth of the natural population is constrained by the environmental carrying capacity K. When the population size reaches the K value, it will no longer grow, that is,

$$\frac{dN}{dt} = 0 \tag{1}$$

Assume the impact of reducing population growth rate is simple, that is, its impact gradually and proportionally increases with increasing density. For example, every additional individual in a population has a $\frac{1}{K}$ impact on the growth rate, or in other words, each individual utilizes $\frac{1}{K}$ of space. If there are N individuals in the population, $\frac{N}{K}$ of space is utilized, and there is only $(1-\frac{N}{K})$ of remaining space available for sustained growth. In this way, a mathematical model for population growth can be derived.

$$\frac{dN}{dt} = rN(1-\frac{N}{K}) \tag{2}$$

Among them, N represents the population size, r is the instantaneous growth rate of the population, t is time, and K is the environmental capacity.
The integral form of this equation is:

$$N_t = \frac{K}{1+e^{a-rt}} \tag{3}$$

2.2. The Logistic model corrected by sex ratio

The variable sex ratio was introduced to study the impact of sex ratios variation on the population size of lampreys. Assuming that the sex ratio of the lamprey is 1:1, the females account for 50% of the total population, the coefficient of growth rate (r) is 1. Because male number increase can reduce the number of females, which can negatively impact the reproductive efficiency. Thus, Pm (male propotion in the population) was induced to measure the impact of sex ratio. The model is as follows:

$$N_t = \frac{K}{1+e^{a-r\frac{50\%}{p_m}t}} \tag{4}$$

2.3. The model evaluating the effects of lamprey population on the stability of ecosystem

An ecosystem possessing ecological equilibrium has the capacity returning to its equilibrium state after a perturbation or does not experience unexpected large changes in its characteristics across time. r_1 is the capacity of an ecosystem to maintain equilibrium status when being disturbed. The measurement of r_1 is a result of x_1 divided with x_2,

$$r_1 = \frac{x_1}{x_2} \tag{5}$$

the x_1 is stutus of an ecosystem after the disturbance and x_2 is the status of the ecosystem before the disturbance.

the degree of change in a population is ,

$$x_1 = \frac{N_1}{K} \tag{6}$$

where N_1 represents the reduced population size due to disturbance, $x_1 \in (0, 1)$. The $\frac{N_1}{K}$ eliminates the size differences between populations.

According to Logistic model described in equion (3), the x_1 is

$$x_1 = \frac{a - \ln(\frac{k}{x_2} - 1)}{r} \tag{7}$$

Thus the variation degree of a population after disturbance is ,

$$x_1 = \int_0^x f(x) \tag{8}$$

$$f(x) = \frac{N_1}{K} \tag{9}$$

where *x* is the disturbance amplitude, which will be derived below.

One assumption here is that the effect of the stability of different populations on ecosystem stability is roughly determined by quantity, and the stability of the population's resistance is only related to its quantity, thus for the x_1 of this ecosystem,

$$x_1 = \sum_{i=1}^{n} n_i * x_{1i} \tag{10}$$

where x_{1i} represents the i-th population,

$$n_i = \frac{n}{N} \tag{11}$$

where n represents the population of a certain specie and N represents the population of the whole ecosystem. While, n_i represents the ight of the i-th population on the x_1 according to the population proportion.

The following is the derivation of the x_2. The disturbance indicator is considered as the change in the number of lampreys, along with any additional indicators. To eliminate differences between different ecosystems, the change in the number of lampreys is expressed as a percentage, leading to the final outcome.

$$x_2 = \frac{\Delta n}{N} \tag{12}$$

Δn is the change in the number of lampreys, where N represents the original population size of lampreys. A equation is finally obtained.

$$r_1 = \frac{x_1}{x_2} = \frac{\sum_{i=1}^{n} n_i * x_{1i}}{\frac{\Delta n}{N}} \tag{13}$$

Using this equation, the impact of changes in the number of lampreys on ecosystem stability could be measured from a quantitative perspective.

3. Results

3.1. Population dynamic of sea lamprey at different sex ratio

The Sea lamprey population danamic was simulated using the equation 4 at the 1:1, 7:3, and 3:7 male to female ratios. The results show that the sex ratio has a significant impact on the population dynamic of the Sea lamprey. At 1:1 male to female raio, the population of Sea lamprey increase until approaching the carrying capacity, then it fluctuate arroud the carrying capacity, which fits for the

logistical population increasing model (Fig.1-A). At 3:7 male to female ratio, the population shows a significant decresing trend (Fig.1-B). At 7:3 male to female ratio, the populations shows a undulant decreaseing trend, in which the population increase to the 1.2 then decrese (Fig. 1-C). The above results indicate that equal sex ratio may make the Sea lamprey maintain a relatively higher population size, which will make the food availability to the individuals decrease and some individuals could not survive. When the male mortality higher than that of the female, the sex ratio may become female dominant, then the population size will decrease significantly. When the female mortality higher than that of the male, the sex ratio may become male dominant, then the population size will show a fluctuation trend. In natural condition, food shortage may adverse to the female survival, thus the model at male dominant can reflect the real population dynamic.

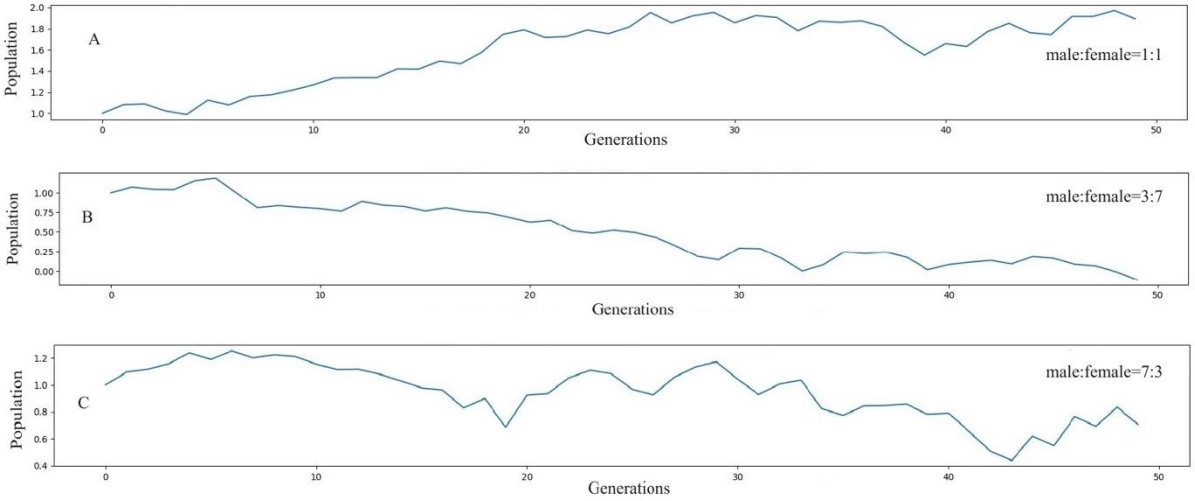


Figure 1 Sea lamprey population dynamic at the the equal (A), female-dominant (B) and male-dominant(C) sex ratios.

3.2. The effect of sex ratio on the stsbility of ecosystem

According to the equation (4) and (13), the female and male dominant population dynamic of the Sea lamprey and the ecosystem stability were simulated (Fig. 2). The variation of ecosystem stability is consistent with the variation of the population size of the female dominant population, while the variation of the stability is oppsite to variation of the population size of male dominant population. These results indicate that the stability of an ecosystem is generally in the opposite direction to the male ratio and maintaining the growth of female lampreys can to some extent ensure the stability of the ecosystem. The male ratio of the population increase make the population of lamprey decrease, inducing the fish host increase thus the stability of the ecosystem decrese. When the fish population increase, the food availability to the lamprey individual increase, which can support more females and lamprey population increase. Decreasing of the male ratio make the lamprey population increase, which induce fish population decrese and ecosystem stability increase. Thereby, the sex ratio of the sea lamprey population is an important regulator of the ecosystem stability in a closed lake. Managing the river and lakes where the lamprey breed and live in order to limit the juvenile lamprey in a closed lake could naturally maintain the lamprey and fish population in a stable fluctuation.

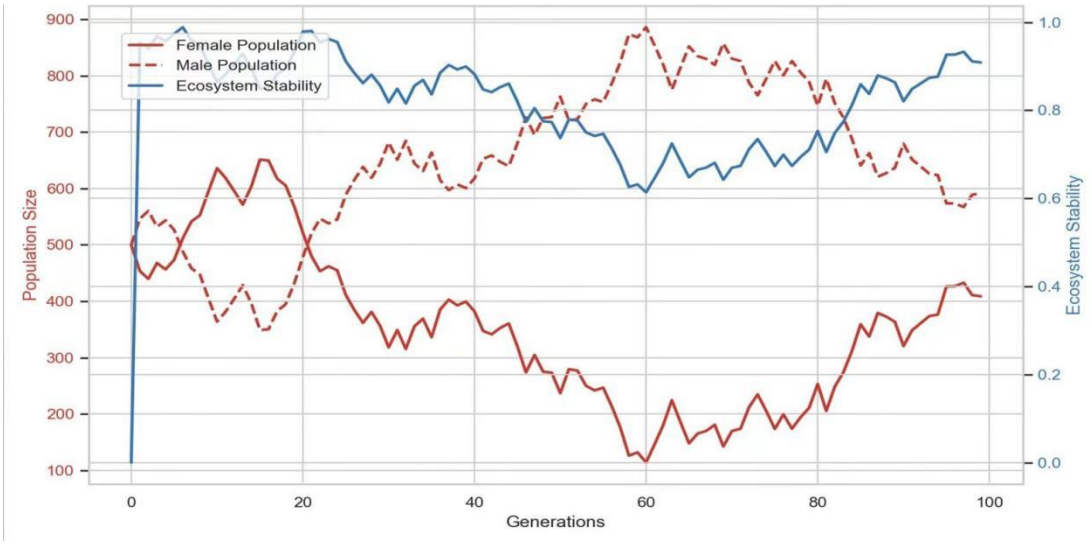


Figure 2 Population dynamics of Sea lamprey at male and female dominance and the ecosystem stability.

4. Conclusions

In this article, a sex ratio corrected logistic population growth model and a ecosystem stability model were established, in which the growth rate is influenced by sex ratio and the stability was measured by the capacity of a population returning to the equilibrium state after a perturbation. The results of simulations using these models indicate that the lamprey population show an undulant decrease trend when the male ratio increase, which is more ecologically relevant than the prediction using the typical logistic model. The male ratio of the lamprey population is an important factor regulating the ecosystem stability in a closed lake. Decreasing of the male ratio can increase the ecosystem stability. Managing the river and lakes where the lamprey breed and live to avoid lamprey dispersal between lakes could naturally maintain the lamprey and fish population in a stable fluctuation.

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