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Interaction model between sea lampreys and ecosystem based on Logistics model

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Abstract. An interaction model between lampreys and ecosystem based on logistic equation is established. By solving the differential equations, the sex ratio of lampreys varies with the number of other populations, the number of its own population and the growth rate. The results suggest that changes in the sex ratio will give lampreys an advantage in population competition and inhibit the development of other populations.Logistics equations to study the performance of lampreys in population competition, and environmental equations to discuss lampreys management plans. This has practical implications for dealing with invasive species in the Great Lakes and elsewhere. In addition, we studied and built models to explore the pros and cons of species being able to change their sex ratios in response to resource availability and gain insight into the resulting ecosystem interactions.

Keywords: Logistics, Differential Equations, Sea lampreys.

1. Introduction

A former Marine lamprey became an invasive species after it was accidentally introduced into North America's Great Lakes. Because the adult East Asian forked lampreys survive by feeding on the blood of other fish, their invasion has taken a toll on the Great Lakes fisheries, especially the lake pinhead and Baikal whitefish. The sex ratio of lampreys depends on the environment [1]. Their growth rate during the larval stage determines the sex of the adult lampreys. When the environment is unfavorable and the growth is slow, the male proportion can reach 78%. In contrast, the proportion of men is about 56%. [2] In this context, we studied the sex ratio of lampreys and its dependence on the environment [3]. We creatively use logistic equations to study the performance of lampreys in population competition and add environmental equations to discuss lampreys management options. This has important practical implications for dealing with invasive species in the Great Lakes and beyond. In addition, we studied and built models to explore the pros and cons of species being able to change their sex ratio in response to resource availability [4] and to gain insight into the resulting ecosystem interactions.

2. Establishment of differential equations based on Logistics model

2.1. Equation of influence of environmental variables on sex ratio

Firstly,due to the influence of extreme weather and greenhouse effect in recent years, the effect of temperature on the sex ratio is first considered[5].The temperature and sex ratio meet the following equation:

$$r(T) = aT^2 + bT + c \tag{1}$$

where T represents temperature.

Then considering the impact of environmental resources on sex ratio, the Verhulst model of sex ratio growth is constructed in the case of limited environmental resources (i.e. food supply)

$$\frac{\mathrm{d}A}{\mathrm{d}t} = r(T)A\left(1 - \frac{X_1}{K}\right) \tag{2}$$

where A, r and T represent the sex ratio, growth rate and temperature respectively α is the saturation parameter of sex ratio growth and is related to food supply. In summary, the effects of environmental factors on the sex ratio of lampreys can be expressed as the following differential equation[6]:

$$\frac{\mathrm{d}A}{\mathrm{d}t} = (aT^2 + bT + c)A\left(1 - \frac{X_1}{K}\right) \tag{3}$$

2.2. Equation of effects of sex ratio on ecosystem

For lampreys population,X_1 is used to represent the population number, so in waters with limited environment and resources, the relationship of lampreys population growth should conform to the Logistics model:

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} = r_1X_1\left(1 - \frac{X_1}{K_1}\right) \tag{4}$$

where A, r, T, K_1 represent the sex ratio, growth rate temperature and Environmental capacity respectively. $1 - \frac{X_1}{K_1}$ represents the population size that can be accommodated under limited resources and environment. In the Great Lakes region, sea lampreys lack natural predators, and the interspecies relationship is mainly parasitic and competitive. For the crustacean X_2, which is also an invasive species, the species size change can also be represented by Logistics model:

$$\frac{\mathrm{d}X_2}{\mathrm{d}t} = r_2X_2\left(1 - \frac{X_2}{K_2}\right) \tag{5}$$

Crustaceans partially overlap with lampreys in food and living areas[3], so crustaceans and lampreys form a competitive relationship, and the growth of the two scales has an inhibitory effect on each other. The size change of lampreys at this time can be expressed

as:

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} = r_1X_1\left(1 - \frac{X_1}{K_1} - a_{12}\frac{X_2}{K_2}\right) \tag{6}$$

where K_1, K_2, a_{12} represent the environmental tolerance of lampreys, the environmental tolerance of crustaceans, and the impact of the second population on the first population, respectively.

The size change of crustaceans can be expressed as:

$$\frac{\mathrm{d}X_2}{\mathrm{d}t} = r_2X_2\left(1 - \frac{X_2}{K_2} - a_{21}\frac{X_1}{K_1}\right) \tag{7}$$

Further, if we continue to increase the number of populations with interspecific rela- tionships, we can obtain the following differential equation:

$$\frac{\mathrm{d}X_i}{\mathrm{d}t} = r_iX_i\left(1 - \frac{X_i}{K_i} - \sum a_{ij}\frac{X_j}{K_j}\right) \tag{8}$$

WhereK_I and a_{ij} respectively represent the environmental capacity of population i and the influence degree of population j on population i.

Finally, the population growth rate of lampreys should meet:

$$\frac{dr_1}{dt} = \alpha_3 r_1 A\left(1 - \frac{A}{K}\right) \tag{9}$$

A system of differential equations can be obtained by combining the above equations:

$$\begin{cases} \frac{dA}{dt} = (aT^2 + bT + c)A\left(1 - \frac{X_1}{K}\right) \\ \frac{dX_1}{dt} = r_1 X_1\left(1 - \frac{X_1}{K_1} - a_{12}\frac{X_2}{K_2}\right) \\ \frac{dX_2}{dt} = r_2 X_2\left(1 - \frac{X_2}{K_2} - a_{21}\frac{X_1}{K_1}\right) \end{cases} \tag{10}$$

Where A, T, K_1, K_2, r_1, r_2 represent sex ratio, temperature, environmental capacity of the two populations, and growth rate of the two populations respectively.

2.3. The value of a constant termin a differential equation

2.3.1. Equation 3 Determination of environmental parameters

Firstly, the effect of temperature on the growth rate of sex ratio is considered, and Equation 1 is introduced.

According to the literature, the preferred water temperature of lampreys in the Great Lakes is about 3°C 20°C, and lampreys reach their maximum growth at 15°C, so the symmetry axis of r (T) is $T = -\frac{b}{2a} = 15$, where a < 0. At 0°C, lampreys are not suitable for survival, and the sex ratio growth rate of lampreys is 0, so C = 0. Therefore, we can determine that a=-0.0005; b=0.015[7]. Subsequently, in a scenario characterized by limited environmental resources (specifically, food supply), we will establish a Verhulst model for the growth of gender ratios.

For Equation 9, α_3 represents the saturation parameter for gender ratio growth, which is related to food supply; K stands for the maximum capacity ratio of female sea lam- preys that the environment can accommodate. We have found relevant literature and determined that $K = 0.5, \alpha_3 = 0.5$.

2.3.2. Equation 6 and 7 Determination of competition parameters

Equation 6 and equation 7 are treated in a similar way, so they are treated together. Because only a small area is studied, the environmental capacity of the population can be directly specified:$K_1 = 100, K_2 = 100$.

For K Essay topic Field study suggests that sex determination in sea lamprey is di- rectly influenced by larval growth rate Nicholas S. Johnson,1 William D. Swink,1 and Travis O. Brenden2.

For example, prior to the initiation of large-scale efforts to control invasive sea lamprey (Petromyzon marinus) adult populations in the upper Laurentian Great Lakes (Lakes Su- perior, Huron, Michigan) were predominately male-biased (approx. 65% male). After control efforts reduced sea lamprey populations by 90%, adult sea lamprey populations became female-biased (approx. 40% male).The annual growth rate of sturgeon in the lake over time is shown in Figure 1.

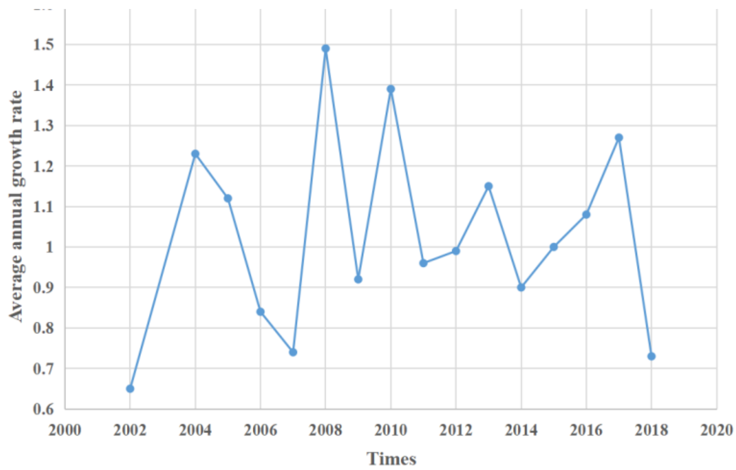

Figure 1: Annual growth rate of lake sturgeon over time.

We predict the maximum growth rate of lakestur- geon without the intervention of external conditions. We first find the average of this set of data.

$r_2 = \frac{\Sigma\lambda_I}{16} = 0.5$, We then calculated the variance of this set of data .

$\sigma^2 = \sqrt{\frac{\Sigma(\lambda_i - x)^2}{16}} = 0.05342$, and found that the variance obtained was very small, indi- cating that the stability of this set of data was high. Therefore, we use the average of this set of data to represent the maximum growth rate of lake sturgeon[8].

2.3.3. Parameter determination of Equation 9

Equation 9 describes the relationship between the natural growth rate of lampreys population r_1 and the proportion of females A_1in the population Figure 2 shows the estimate of the number of lamprey adults in recent years[9]. The change of the number of adults is approximately regarded as the change of the population number of lamprey, so the population growth rate of lamprey in recent years can befitted.The estimated population of adult lampreys is shown in Figure 2.

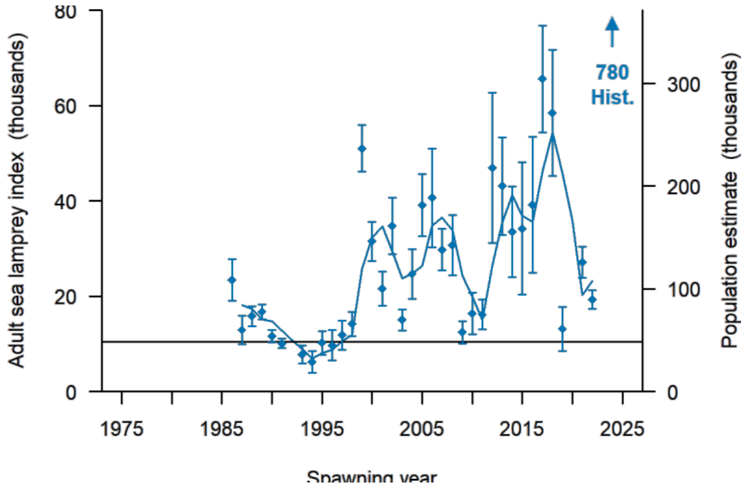

Figure 2: Population of adult lampreys [9]

Tabular data of tagged recapture of lampreys in the Great Lakes region (see Appendix 1 for detailed data) were used to obtain the sex ratio curve of lampreys in recent years is shown in Figure 3.

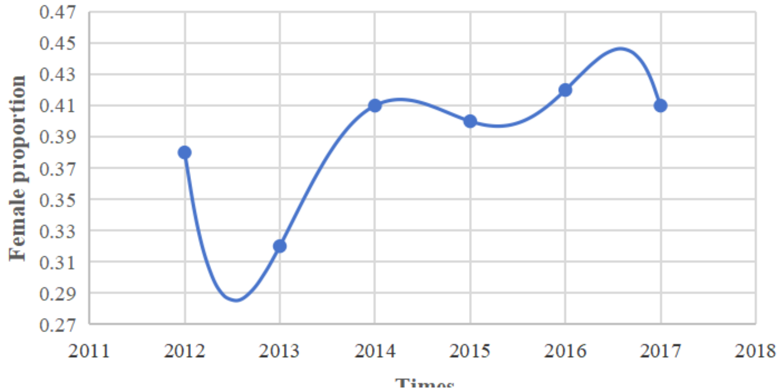

Figure 3: Sex ratio change curve of lampreys

The proportion of female lampreys continued to decline between 2012 and 2013 when lampreys had less food. From 2013 to 2014, the ratio of female lampreys continued to rise, and from 2014 to 2017, the ratio of female lampreys fluctuated around 0.41. It was determined that the lampreys had an adequate food source during this time. At the same time, we can also conclude that when the lampreys population reaches a stable state, the ratio of female lampreys is about 0.41.

By integrating Equation 9, we get:

$$r_1 = \alpha_3 At + c \tag{11}$$

According to the year, the above population growth rate and the proportion of sex change were obtained by curve fitting: α_3 =0.5.

3. Result analysis

We have established differential equations to express the local ecosystem of lampreys in the context of the Great Lakes, and have explained and obtained the coefficients in the differential equations. In particular, for Equations 6 and 7 to represent the inter- species relationship, that by adjusting the symbiosis coefficients $[a_{12}, a_{21}]$ which is shown in table 1 and giving different values, the effects of changes in the sex ratio of lamprey on the population numbers of different populations in the ecosystem can be obtained. The specific relationship between coefficient pairs and the overall population is shown in Table 1.Since lampreys have no obvious predators and reciprocity is rare, we'll focus on competition next.

Table 1: The value of the interspecific coefficient under the interspecific relation

a	$a_{ji} < 0$	$a_{ji} = 0$	$a_{ji} > 0$
$a_{ij} < 0$	Mutual benefit	Commensal relationship	Predation relationship
$a_{ij} = 0$	Commensal relationship	Mutual neutrality	Bias relation
$a_{ij} < 0$	Predation relationship	Bias relation	Competitive relationship

3.1. Weakly competitive populations with lampreys

The symbiosis coefficient pairs [0.2,0.7] were used to represent small omnivorous fish in the Great Lakes that partially overlap with lampreys in their food source living space[10], but have a simple food structure and are less aggressive and thus less competitive against lampreys.

It can be seen from Figure 4 that with the change of the sex ratio of lampreys, the pop- ulation of X_2 first increased and then decreased rapidly. It can be predicted that with the further change of the sex ratio, the population of X_1 will still have a trend of decreasing, and the resources enjoyed by the population of X_1 will further decrease, and there is a risk of extinction. Lampreys, on the other hand, continue to increase steadily, to a certain extent in a linear relationship, regardless of other predators, and the trend has exceeded the ability of the environment to regulate, which will have an impact on local fisheries.

The weak competitive population competed with lampreys for limited natural re- sources and began to have sufficient natural resources. The numbers of the two popu- lations showed a rapid increase, and with the growth of the population, they began to compete with each other and restrain each other. The population growth rate began to decline rapidly into negative territory, and eventually lampreys gained most of the re- sources. The highest point on the way is the point where the population growth rate is zero.

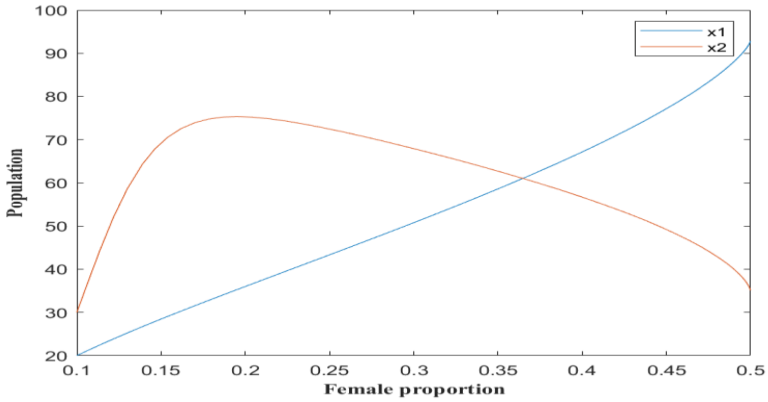

Figure 4: Image of vulnerable populations competing with lampreys

3.2. Moderately competitive population with lampreys

Use the symbiotic coefficient pairs [0.5,0,5] to represent crustaceans in the Great Lakes. As invasive species, they both have strong reproductive ability and no obvious natural enemies, so their competitiveness is similar.

It can be seen from Figure 5 that with the change of the sex ratio of lampreys, the popu- lation numbers of both species have a highrise, and they coincide at the same point below the environmental capacity in the final state, indicating that the competition between the two species has inhibited the growth of each other but will not cause large-scale popu- lation death. It is worth noting that both of them, as invasive species, will have a huge impact on the local ecology.

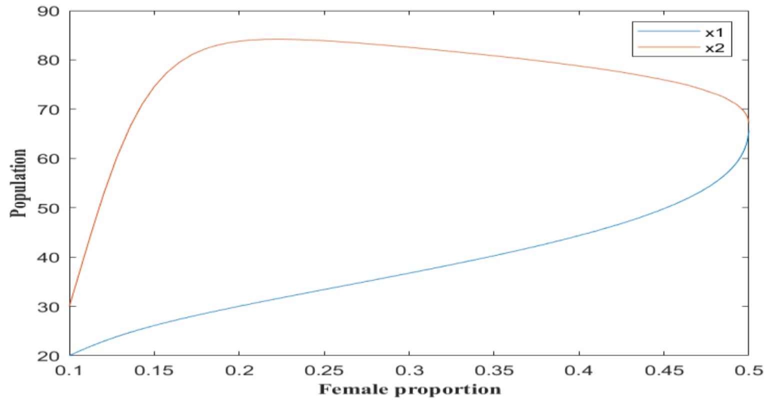

Figure 5: Image of moderately competitive population with lampreys

The medium competitive population competed with lampreys for limited natural re- sources and began to have sufficient natural resources. The numbers of the two popu- lations showed a rapid increase, and with the growth of the population, they began to compete with each other and restrain each other.

The rate of growth starts to decline until it turns negative,and at the final overlap point, the two share natural resources equally.

3.3. Highly competitive population with lampreys

The symbiosis coefficient pairs [0.7,0.2] were used to represent a type of aggressive fish that partially overlacks with lampreys in the food source living space, but is highly aggressive and has a wider food structure, and is more competitive against lampreys.

As can be seen from Figure 6, with the change of the sex ratio of lampreys, the X_2 population first increased rapidly, indicating that it indeed occupied the development resources of lampreys to a certain extent, and then tended to stabilize. Although the population of lampreys increased slowly, it remained stable at a certain level and had a certain upward trend. The predictable and unique sex ratio of lampreys ensured the continuation of its population, and at the same time inhibited competitive homotrophic organisms to a certain extent, and protected biodiversity, which had positive significance for the stability.

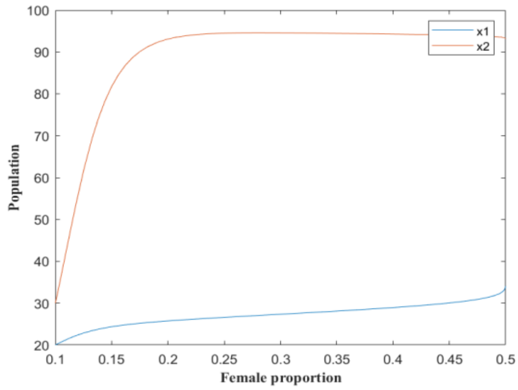

Figure 6: Image of vulnerable populations competing with lampreys

The highly competitive population competed with lampreys for limited natural re- sources, and the natural resources were abundant at the beginning, and the numbers of the two populations showed a rapid increase, and with the growth of the population, they began to compete with each other and restrain each other. The growth rate of the population gradually leveled off and eventually the population got most of the resources of the ecosystem.

3.4. Effects of sex ratio changes on the growth rate of sea lampreys

Figure 7 shows that under normal conditions, the sex ratio of lampreys is positively correlated with the growth rate. In this example, the approximately linear relationship is shown, indicating that the sex ratio has a positive and relatively large impact on the population growth rate.

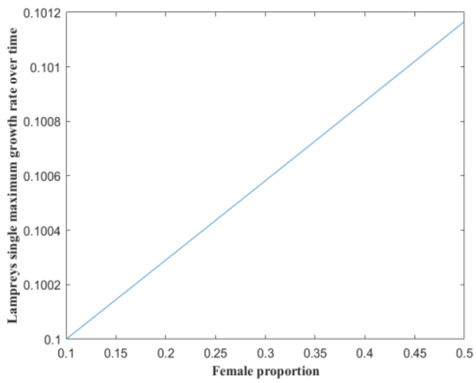

Figure 7: Effect of sex ratio change on growth rate of sea lampreys

4. Conclusion

In summary, we simulated the performance of lampreys populations in competition with different species by establishing a system of differential equations for lampreys, and found that the unique sex ratio mechanism of lampreys can help populations reproduce rapidly in an environment devoid of competition, and gradually destroy the local native species without human intervention over a certain period of time, thus undermining the stability of the ecosystem. This is consistent with the current situation of lampreys flooding in the Great Lakes and other regions of the United States. In addition, it can also maintain the continuation of the population in a highly competitive environment, and has a strong ability to resist pressure. In its native environment (such as the Atlantic Ocean), it has a certain role in maintaining species diversity and ecosystem stability. Through this study, part of the internal mechanism of lampreys species invasion is revealed, and researchers can control the sex ratio of lampreys population through hormones and other means to control its reproduction. Further in the future, by studying the effects of this particular sex ratio change on biological populations, there are great possibilities for endangered animal protection and species invasion prevention.

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