Problem Chosen	2024 MCM/ICM Summary Sheet	Team Control Number
A		2407463

Male or female?Sex ratio is influencing the ecosystem

Summary

The sex ratio of most species in the biosphere is 1:1, but some species have adaptive sex variation mechanisms, so the sex ratio changes according to the external environment.Using lampreys as an example, we attempt to **investigate the "coupling" relationship between sex ratios and the environment**, and explain **the advantages and disadvantages of species changing their sex ratios in response to resource availability.**

First, we selected lampreys and other species in the lake ecosystem of the Great Lakes as research objects. **Based on the Lokta-Volterra model, considering the complexity of biological population interaction and human factors affecting the appropriate introduction of parameters**, we improved it to obtain a differential equation model of lampreys preys on lake trout and Atlantic salmon. Then we use it to study complex interspecific relationships.

Then, **a growth rate model of lampreys was established**, which mainly considered **the effects of resource amount and temperature on growth rate**, in which temperature affected growth rate by affecting metabolic enzyme activity in lampreys.According to the growth rate, **a Soft-Voting integrated classifier containing Logistics, K-nearest neighbors, BP Neural Network, Support vector and other binary classification models** is used to accurately classify the sex of lampreys, which reflects strong robustness.

In order to study **the effect of lampreys sex ratio on ecosystem stability**, we first used **a cellular automaton(CA) that introduced river flow and ecosystem self-repair mechanism**, and carried out mesh diffusion, flow and repair respectively according to the set diffusion, flow and self-repair parameters.Multi-generation individual iterative simulation was performed according to the set maximum number of iterations to simulate the impact on ecosystem stability.Then we collected the relevant data of the factors affecting the stability, carried out **factor analysis to reduce the dimension, extracted the principal components, and then carried out fitting and regression** to obtain the influence of the sex ratio of lampreys on these factors.

In order to assess the impact of these factors on ecosystem stability, we used **three different weighting methods based on the AHP evaluation method to obtain more robust factor weights**, and put forward targeted governance recommendations accordingly.

Based on the differential equation model of predation of lake trout by lampreys, we also introduced a differential equation model of the relationship between single parasitic parasite and lake trout population. In addition, combined with the literature reviewed, we qualitatively analyzed the effects of sex ratio changes of lampreys on different species of parasites.

Keywords: Lotka-Volterra Model, Soft-Voting Classifier,Cellular Automata,AHP Analytic Hierarchy Method,Factor Analysis,Ecosystem Interaction

Contents

1 Introduction

1.1 Problem Background

In some lake habitats, there is a parasite named lamprey that has a significant impact on the ecological environment.Lampreys live in lake or marine habitats and migrate along rivers to spawn.The eggs of lampreys develop into the blind larval form, ammocoete.

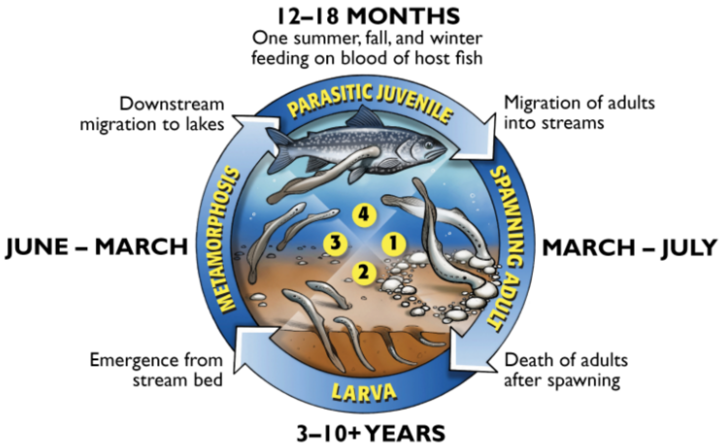

Figure 1: the life circle of lamtrey

The rate of growth in the later larval stage will determine the sex differentiation of the sea lampreys.This growth rate is in turn influenced by the availability of food in the environment.In Settings where food is scarce, the growth rate is lower and the proportion of men can reach about 78 % of the population.In environments where food was more readily available, the proportion of men was about 56% of the population.It is of great significance to study the sex ratio of sea lampreys and the interaction between sea lampreys and ecological environment.

1.2 Restatement of the problem

In order to analyze the advantages and disadvantages of species altering gender ratios based on resource availability, and to gain a deeper understanding of the interactions occurring within ecosystems, the model we develop must:

- Consider the impact of lamprey populations on other organisms within the ecosystem.
- Consider how the gender ratio of lampreys is influenced by the environment.
- Consider the specific mechanisms through which lampreys influence the stability of the ecosystem.

1.3 Our work

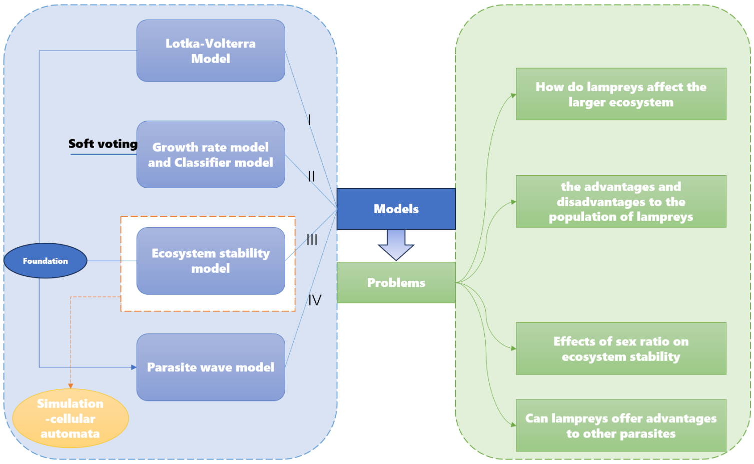

Figure 2: our work

1. Developed a multidimensional predator-prey model (Model I) based on Lokta-Volterra differential equations, considering the predation effects of predators on multiple prey and the competitive effects among prey.
2. Divided the ecosystem into abiotic and biotic factors and used Model I to address the impact of variable sea lamprey sex ratios on the population of its main prey, explaining how it affects the larger ecosystem.
3. Developed an individual growth rate and classifier model for sea lampreys (Model II), considering the effects of resource availability and water temperature on the growth enzyme activity within lampreys and deriving a growth rate-environmental factor model as an intermediary. Classified the growth rate indicators based on resource availability to determine how growth rate influences the sex ratio of sea lamprey populations.
4. Applied Model II to address how individual lamprey sex changes with variable resource availability and analyze the advantages and disadvantages of variable sex ratio in sea lamprey populations.
5. Developed an ecosystem stability model (Model III), using cellular automata to simulate the specific impact of sea lamprey populations on the ecosystem and constructing the relationship between ecosystem stability and multiple important environmental indicators using the AHP hierarchical analysis method.
6. Applied Model III to explain how sea lamprey populations with variable sex ratios affect ecosystem stability.
7. Developed a parasite fluctuation model (Model IV), dividing parasites into those parasitizing sea lamprey populations and those parasitizing other populations, and demonstrating their impact through differential equations to explain whether sea lamprey populations can provide advantages for other organisms.

2 Assumptions and Notations

2.1 Assumptions

- **assumption 1:**The intensity parameter of human fishing lampreys is a fixed value.
  rationality: In order to simplify the model, the number of parameters is reduced to facilitate the running of the program.In the time frame of our study, there were no policies on lampreys fishing and other influences, and the parameters of fishing intensity could be regarded as fixed values.
- **assumption 2:**The sex differentiation time of lampreys is fixed. The body length and weight data of lampreys of different sexes collected at a fixed time point can represent the average growth rate per unit resource amount.
  rationality: According to the life cycle map of lampreys, it can be seen that lampreys develop into adults in January or February, which is the basis for a fixed time of sexual differentiation.The average growth rate is determined by dividing the amount of growth by the time, and when the time is fixed, the amount of growth is proportional to the average growth rate, which can represent the growth rate.
- **assumption 3:**To simplify the model and reduce the difficulty of data acquisition, it is assumed that there is a linear positive correlation between growth rate and resource amount, and that individual female lampreys have a better ability to support parasites.
  rationality: Given that the percentage of females in lampreys increases in an environment where food is more readily available, it is reasonable to assume that females grow faster, have more biomass, and are better able to support parasites.This is also confirmed by our soft-voting binary model for sex classification of lampreys based on their biomass.
- **assumption 4:**The relationship between temperature and growth enzyme activity approximates a parabolic relationship, the relationship between individual growth rate and growth enzyme activity approximates a Logistic curve, and the substrate concentration of growth enzyme action in Lampreys remains approximately constant.
  rationality: By referring to literature , we obtained the curve relationship between temperature and growth enzyme activity, and found that it was approximately in line with the parabolic relationship.The individual growth rate has a certain upper limit, and when the enzyme activity intensity reaches a certain level, the influence on the growth rate is no longer significant.The homeostatic maintenance mechanism of organisms keeps nutrient concentrations approximately constant.
- **assumption 5:**Effects of species richness, lake pH, pollutant concentrations, nitrogen and phosphorus concentrations on ecosystem stability in lake ecosystems.
  rationality: In order to simplify the model and prevent modeling difficulties caused by excessive data dimensions, the above factors were determined by consulting data and basic biological knowledge.Among them, the pH value of the lake water can significantly affect the steady state of the inorganic environment in the ecosystem, the concentration of pollutants can significantly affect the biological community, and the concentration of nitrogen and phosphorus is a factor that must be considered for the growth and reproduction of organisms. At the same time, because it may cause bloom and red tide, it should be considered as a factor

for the stability of the ecosystem.

- **assumption 6:**During the study, no factors such as the invasion of new species and the inflow of alternative organisms caused drastic changes in ecosystem stability.
  rationality: Although we studied an open lake ecosystem, we assumed that the ecosystem would not be affected by these low probability unexpected events in order to simplify the model.

2.2 Notations

Notations	Definition
y	the number of lamtrey in the Great Lakes
x_1	the number of lake trout in the Great Lakes
x_2	the number of atlantic salmon in the Great Lakes
x_3	the number of paratise in lake trout
r_1	mortality of lamtrey as predators
r_2	natural growth rate of lake trout
r_3	natural growth rate of atlantic salmon
e	Parameters of artificial lamtrey fishing intensity
λ	Quantity of resources
λ_{max}	Determine the maximum eigenvalue of the matrix
λ_1	lake trout's ability to provide for lamtrey
λ_2	atlantic salmon's ability to provide for lamtrey
β_1	lamtrey prey on lake trout
β_2	lamtrey prey on atlantic salmon
t	Every time node from 1996 to 2015
α_1	the competition coefficient of lamprey and lake trout
α_2	the competition coefficient of lamprey and atlantic salmon
a	Enzyme activity unit
T	Water body temperature
v	Growth rate per unit of resource quantity
K_1	Growth enzyme activity coefficient

Table 1: Notations Table

3 Task1: Lotka-Volterra Model

3.1 Preparation of the model

In order to analyze the impact of lampreys on the larger ecosystem, we first consulted the data to understand the main distribution locations of lampreys and selected the Great Lakes of the United States as the ecosystem to study.Lampreys play the dual role of predator and prey in this ecosystem.This relates to the case of lampreys as prey for predators and the case of lampreys as prey for prey.

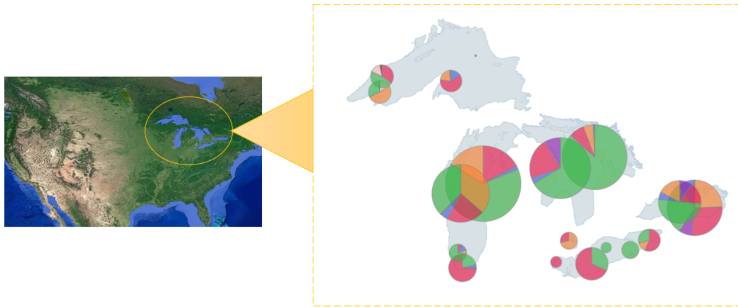

Figure 3: Distribution of major fish in the Great Lakes

By searching publicly available data from the U.S. Department of Agriculture, we found the status of individual fish populations in the Great Lakes and sifted through data from 1996 to 2015.Taking lampreys as the main body to consider, we choose its two main prey A and B.The number of the three was calculated from 1996 to 2015.Of course, lampreys also play the role of prey in the Great Lakes ecosystem.By analyzing the species of fish in the Great Lakes, we find that there are no natural predators of lampreys, so we only consider the effect of human fishing on lampreys.Based on the above work, we completed the data retrieval and sorting.

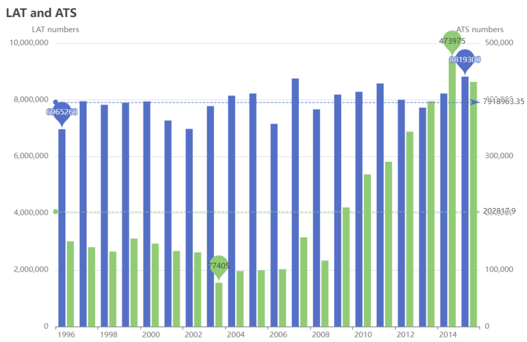

Figure 4: LAT and ATS in Great Lakes

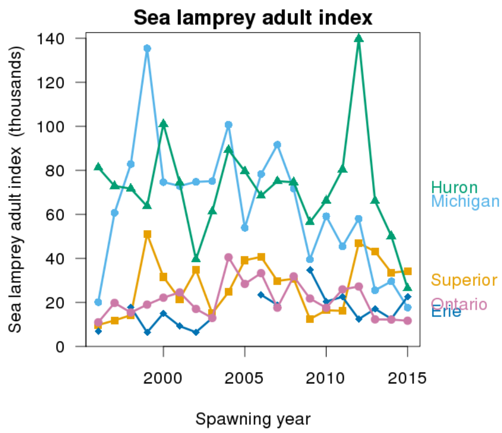

Figure 5: lamprey in Great Lakes

3.2 Establishment of the model

In two parts, we will look at the impact of changes in the population of lampreys on their ecological environment.The following picture is a flow chart of this part of the argument.

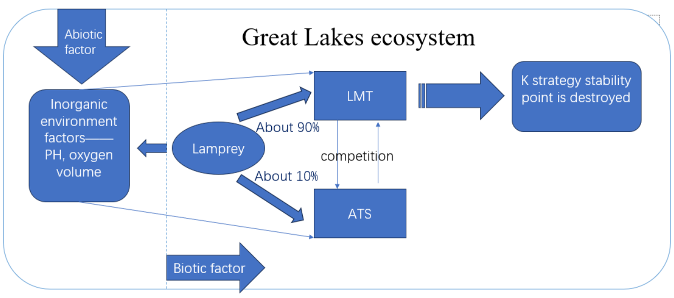

Figure 6: Algorithm flow

Ecosystems are generally composed of biological factors and abiotic factors.Therefore, the impact of lampreys on the ecosystem should also be considered from two parts: the impact on biological factors and the impact on abiotic factors.According to the selection and retrieval of data mentioned above, we mainly took LAT and ATS into consideration of the influence of biological factors, and obtained the direct impact of lampreys on the ecosystem.After consulting a lot of data, we mainly took the changes of lake PH value and dissolved oxygen into consideration of the influence of abiotic factors, and obtained the indirect impact of lampreys number on the ecosystem.

3.2.1 Direct influence

The direct impact of lampreys on an ecosystem can be analyzed from the impact of biological factors in this ecosystem.Let's start with the food chain in the Great Lakes ecosystem, as shown below.

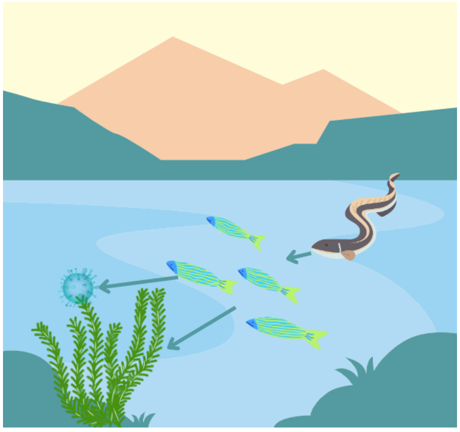

Figure 7: A simplified chain of lampreys

In the Great Lakes ecosystem, lampreys play both predator and prey roles.As predators, lampreys prey directly on LAS and ATS.As prey, the Great Lakes ecosystem contains no natural predators of lampreys.So we mainly consider the effects of human fishing.

The populations in the same ecosystem usually show a series of relationships such as competition, predatory nature, parasitism and symbiosis.In order to better establish the Lotka-Volterra model, we make the following three assumptions:

- At the beginning, the populations of Lampreys, LAT and ATS were y, x_1 and x_2, respectively.
- The growth of each population is restricted by the logistic law.It is assumed that the natural growth rates of Lampreys, LAT and ATS arer_1, r_2 and $r_3$espectively.And the survival limits of the three populations can only be maintained under the constraint of unified resources and environment are K_1, K_2 and K_3, respectively.
- Three populations depend on the same resource to survive, and the greater the number of these three populations, the less resources are available. Thus reducing the population growth rate of the species.With the increase of population number, the increment of each population will have a certain limiting effect on the change of the other population.

The growth rate of the three populations can be expressed as:

- $r_1^{`}(1-\frac{y}{K_1})y$
- $r_2^{`}(1-\frac{x_1}{K_2})x_1$
- $r_3^{`}(1-\frac{x_2}{K_3})x_2$

The relationships between the three populations are expressed as:

- Lamprey preys on LAT.
- Lamprey preys on ATS.
- LAT competes with ATS.

Based on this, we build the Lotka-Volterra model.

$$\begin{cases} \frac{\mathrm{d}y}{\mathrm{d}t} = y\left[-(r_1+e)+\lambda_1 x_1+\lambda_2 x_2\right] \\ \frac{\mathrm{d}x_1}{\mathrm{d}t} = x_1(r_2-\beta_1 y-\alpha_1 x_2) \\ \frac{\mathrm{d}x_2}{\mathrm{d}t} = x_2(r_3-\beta_2 y-\alpha_2 x_1) \end{cases} \tag{1}$$

At the same time, using the retrieved and processed data, we make a preliminary estimate of nine parameters by linear least square method.

$$\begin{cases} \frac{\mathrm{d}y}{\mathrm{d}t} = -(r_1+e)y+\lambda_1 x_1 y+\lambda_2 x_2 y \\ \frac{\mathrm{d}x_1}{\mathrm{d}t} = r_2 x_1-\beta_1 x_1 y-\alpha_1 x_1 x_2 \\ \frac{\mathrm{d}x_2}{\mathrm{d}t} = r_3 x_2-\beta_2 x_2 y-\alpha_2 x_1 x_2 \end{cases} \tag{2}$$

$$\begin{cases} \frac{y_{k+1}-y_k}{t_{k+1}-t_k} = -(r_1+e)y+\lambda_1 x_1 y+\lambda_2 x_2 y \\ \frac{x_{1,k+1}-x_{1,k}}{t_{k+1}-t_k} = r_2 x_1-\beta_1 x_1 y-\alpha_1 x_1 x_2 \\ \frac{x_{2,k+1}-x_{2,k}}{t_{k+1}-t_k} = r_3 x_2-\beta_2 x_2 y-\alpha_2 x_1 x_2 \end{cases} \tag{3}$$

$$\begin{bmatrix} -y_k & x_{1k}y_k & x_{2k}y_k & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_{1k} & -x_{1k}y & -x_{1k}x_{2k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & x_{2k} & -x_{2k}y_k & -x_{1k}x-2k \end{bmatrix} \cdot \begin{pmatrix} (r_1+e) \\ \lambda_1 \\ \lambda_2 \\ r_2 \\ \beta_1 \\ \alpha_1 \\ r_3 \\ \beta_2 \\ \alpha_2 \end{pmatrix} = \begin{bmatrix} \frac{y_{k+1}-y_k}{t_{k+1}-t_k} \\ \frac{x_{1k+1}-x_{1k}}{t_{k+1}-t_k} \\ \frac{x_{2k+1}-x_{2k}}{t_{k+1}-t_k} \end{bmatrix} \tag{4}$$

According to the obtained differential equation model, we successfully drew the change curves of the three populations in a certain period of time, as shown in the figure below.

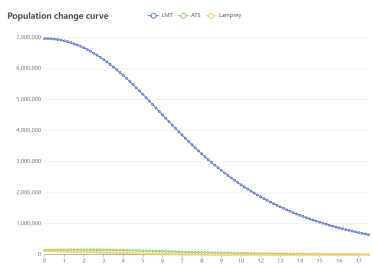

Figure 8: the change curves

3.2.2 Indirect influence

Looking through a lot of data, we found that the presence of lampreys affects the PH of their environment.We're still looking at the Great Lakes as an ecosystem.

Lampreys parasitism.For one thing, in their parasitic life, lampreys release more carbon dioxide than other organisms.On the other hand, the presence of parasites means additional consumption of dissolved oxygen in the Great Lakes, which reduces the amount of dissolved oxygen in the Great Lakes, leading to a decrease in the environmental capacity of the Great Lakes.This is why ATS has not achieved significant growth in numbers in the face of the rapid demise of LAT.

3.3 Some analysis of result

According to figure 8,the number of LAT decreases and the number of lamprey remains stable.According to the information, individual sea lampreys will die shortly after spawning, leading to a stable population size.

The LAT population suddenly declined, while ATS and Lampreys populations remained stable.In order to better explain the changing characteristics of the curve in the graph, we introduce the theory of "R strategy" and "K strategy".

When the amount of environmental resources is extremely rich but the environmental system is not stable enough, organisms usually adopt R strategy, that is, there is only a single stable point determined by the upper limit of resources.However, trout, as a vertebrate living in lake ecosystem, has insufficient resources and stable environment, and will adopt K strategy.K strategy means that there are two stable points in the population number, namely K point and X point. When the population number is between the two points, the population number will approach K point determined by the environmental capacity.However, when the population is severely damaged to the point that the population is below the X point, the population will no longer move towards the K point and will tend to die out.

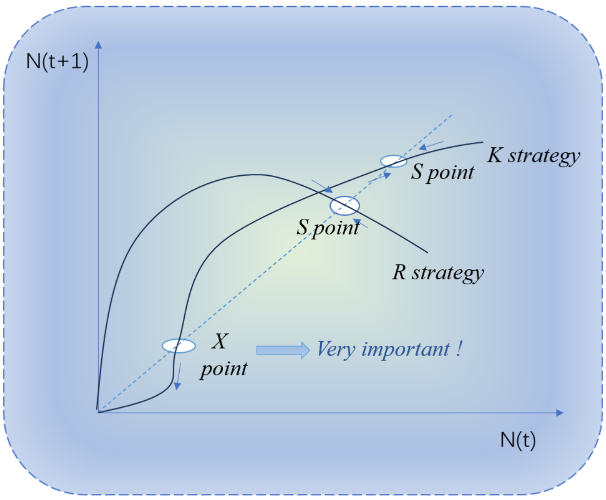

Figure 9: K strategy and R strategy

By looking at the data[2], we found that trout are K-strategy organisms.Its population usually stabilizes near the value k (environmental capacity) of the logistic curve.But because of the abundance of lampreys, lampreys are killing trout in large numbers.As a result, the stable point of the trout population is destroyed, and the population decreases rapidly and is difficult to recover.

4 Task2: Growth Model and Classifier Model

4.1 Growth Model

4.1.1 Preparation of the model

In order to study the advantages and disadvantages of variable sex ratios in lampreys populations, we first need to find the relationship between lampreys' growth rate and important environmental factors.Based on NOAA's lake temperature monitoring data from 2007 to 2013, we have obtained the temperature curve of the Great Lakes over the years with the date.

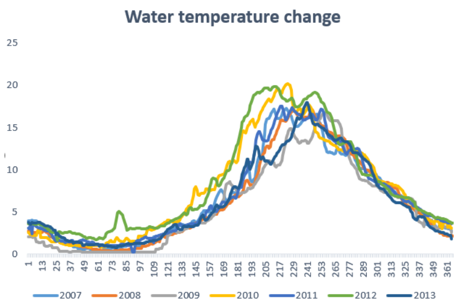

Figure 10: Lake Superior

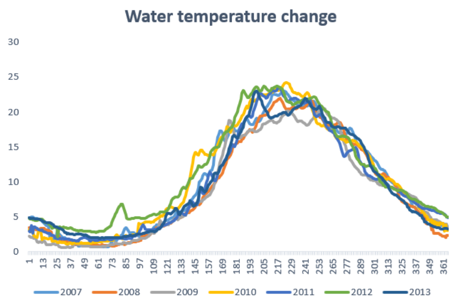

Figure 11: Lake Michigan

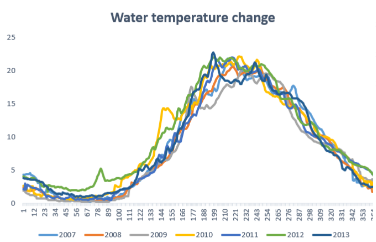

Figure 12: Lake Huron

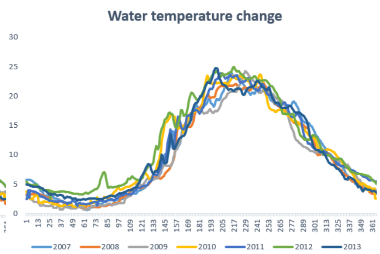

Figure 13: Lake Ontario

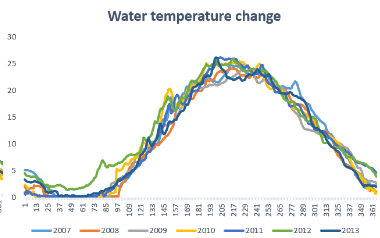

Figure 14: Lake Erie

According to literature[1], we know that water temperature will affect the growth enzyme activities of various biological populations in water, and the relationship is roughly U-shaped within a certain temperature range.Because the growth enzyme will be inactivated at too high a temperature, the enzyme activity is extremely low when the temperature is too low.In this model, we may assume that the relation is a quadratic function with constant term 0.According to the data, we also know that the individual growth rate and growth enzyme activity of lampreys roughly conform to the Logistics curve.

4.1.2 Establishment of the model

Based on the above analysis and hypothesis, we established the functional relationship between growth enzyme activity and temperature, and the functional relationship between individual growth rate and enzyme activity of Lampreys as follows:

$$v = \frac{1}{1 + e^{-a}} \tag{5}$$

$$a = k_1 T^2 + k_2 T \tag{6}$$

$$w = v\lambda \tag{7}$$

The relationship between individual growth rate and temperature of lampreys was obtained.

$$w = \frac{\lambda}{1 + e^{-(k_1 T^2 + k_2 T)}} \tag{8}$$

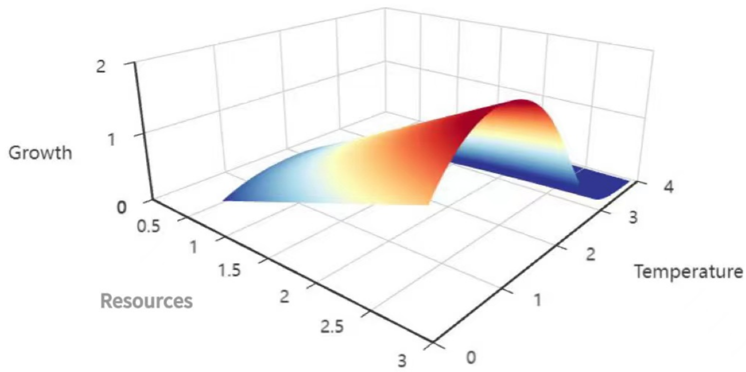

Figure 15: Growth model diagram

The relationship between individual growth of lampreys and water temperature was obtained.

4.2 Integrated Classifier Model(Soft-Voting)

4.2.1 Preparation of the model

We trained by collecting data on the length and weight of lampreys and their respective sex that were farmed and tagged in the Great Lakes.

4.2.2 Establishment of the model

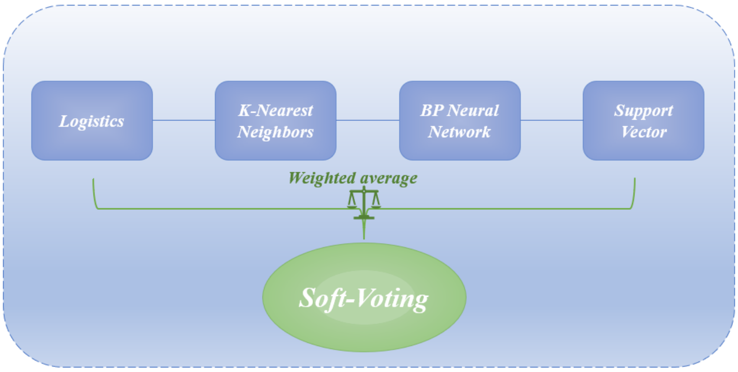

Figure 16: Algorithm flow chart

We set up Soft-Voting classifier to integrate four base classifiers: Logistics classifier, KNN classifier, BP neural network classifier and SVM classifier. By Voting the classification results of the four base classifiers, we can enhance the classification effect of Soft Voting classifier.The specific classification prediction accuracy is as follows:

	Logistics	KNN	BPNN	SVC	Soft Voting
Training set accuracy	0.9310	0.9310	0.9655	0.9310	0.9655
Test set accuracy	0.8947	0.9474	0.8947	1.0000	0.9474
Overall accuracy	0.9167	0.9538	0.9167	0.9583	0.9583

Table 2: the table of prediction accuracy

In order to establish the mathematical relationship between individual growth and sex of lampreys more specifically, we selected the SVM classifier with the best effect among the four base classifiers, and used its decision boundary to represent the relationship between individual growth and sex. The specific expression is as follows:

$$f(x) = sign(w \cdot x^T + b) \tag{9}$$

and

$$x = [\frac{\lambda}{1 + e^{-(K_1 T^2 + K_2 T)}}] \tag{10}$$

After exercising: w=[-0.6487,0.1081],b=106.6342

4.3 Some analysis of result

In view of the advantages and disadvantages of gender change, we can consider the following points.

On the one hand, there are the following advantages:

- Maximizing resource utilization: Lampreys are able to adjust their sex ratio according to the abundance of environmental resources, which helps them maximize the use of available resources.In resource-rich environments, increasing the proportion of females increases the reproductive rate and thus the number of offspring.In resource-poor environments, increasing the male ratio may be better for the survival of the population because males consume fewer resources during reproduction.

- Adapting to environmental changes: Lampreys adapt to changes in their environment by adjusting their sex ratio, which helps them maintain a stable population in an uncertain environment.When environmental conditions change, they can flexibly adjust their breeding strategies to adapt to the new environment.

On the other hand, there are the following disadvantages:

- Reduced genetic diversity: Long-term dependence on environmental resources to adjust the sex ratio may lead to a decrease in genetic diversity of the population.This is because sex ratios are often adjusted based on current environmental conditions rather than on long-term genetic diversity considerations.If the environment changes dramatically and the genetic diversity of the population is low, lampreys may face a greater threat to survival.
- Ecological implications: Adjustments in the sex ratio of lampreys may have implications for other organisms in the ecosystem.As part of the ecosystem, changes in the number and sex ratio of lampreys may affect the stability of the food chain and the survival of other organisms.

5 Task3: Ecosystem stability Model

5.1 Ecosystem simulation of cellular automata

According to the data, the lifestyle of lampreys leads to a decrease in the concentration of carbonate ions in the areas inhabited by lampreys, and lampreys kill a large number of other populations, which has a huge impact on the ecosystem.To investigate the effects of sex ratio changes in lampreys on ecosystem stability, we introduced a cellular automaton model that increases river flow and ecosystem self-healing mechanisms.The process of simulating lampreys' impact on the ecosystem was then completed in the following five steps:

- Initialize the ecosystem and randomly generate the number of lamprey individuals determined by the proportion of females;
- Set impact diffusion function, water flow impact function and ecosystem self-healing function;
- Traversed the grid of the simulation system, searched for individual lampreys, and randomly selected the swimming direction from the black box for diffusion;
- Mark all locations that have been affected by lampreys, locations that have not been affected by lampreys, and locations that are being affected by lampreys;
- Random numbers were extracted, and the grid diffusion, flow and repair were carried out respectively according to the set diffusion, flow and self-healing parameters;
- Conduct multiple generations of individual iterations based on a set maximum number of iterations to simulate the adverse impact on the ecosystem.

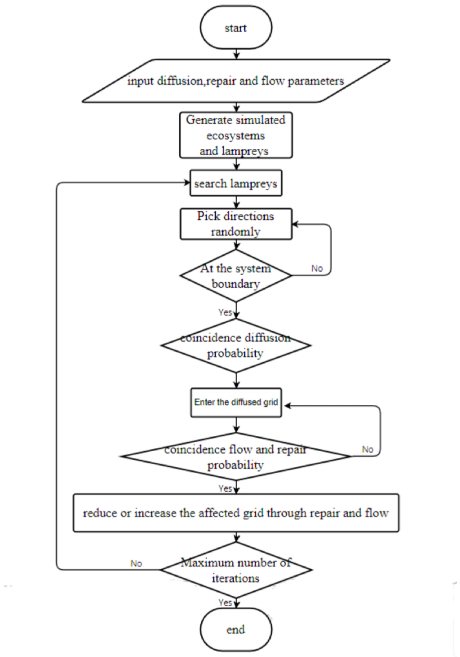

Figure 17: Algorithm flow chart

Through the above simulation, we can see that the existence of lampreys only has a weak impact on the ecosystem at the beginning, but with its movement in the ecosystem, the ecosystem is affected by a large area.

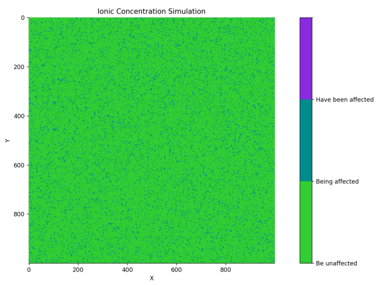

Figure 18: process 1

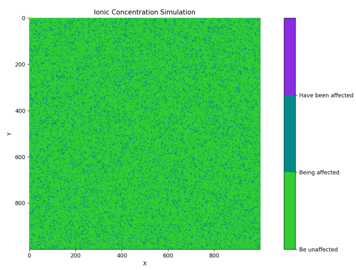

Figure 19: process 2

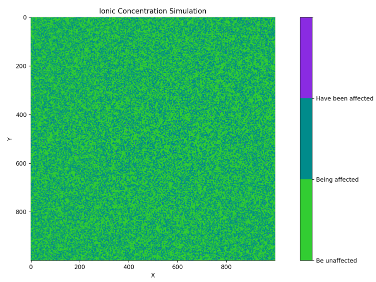

Figure 20: process 3

5.2 Preparation of the model

In order to study the effects of changes in the sex ratio of lampreys on ecosystem stability, we first selected Lake Superior as the ecosystem studied.By referring to the data collected in the literature, we screened and sorted out the data of the sex ratio of lampreys, the content of nitrogen and phosphorus, and the PH value of the lake in 2007 to 2013.

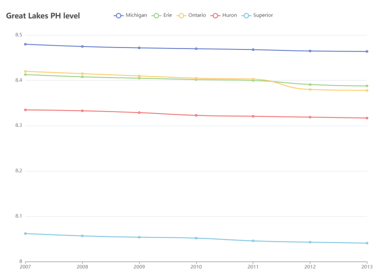

Figure 21: change of PH

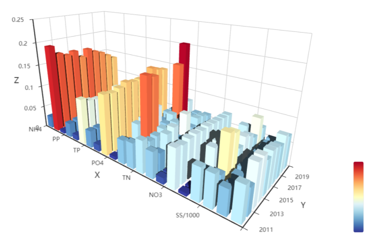

Figure 22: N P content

In the process of data sorting, we found that the time series of the sex ratio data of lampreys did not coincide.Therefore, we used the GM (1,1) model to make a grey prediction of the sex ratio of lampreys to obtain a complete data set for the period 2007 to 2013.

years	2007	2008	2009	2010	2011	2012	2013
Proportion of male lampreys	71.27	68.68	64.42	60.4	56.82	53.52	50.53

Table 3: Proportion of male lampreys

At the same time, in order to ensure the simplicity and stability of the model, we are expected to perform factor analysis on the nitrogen and phosphorus data set.In order to ensure the feasibility of factor analysis, KMO test was performed for the simple correlation coefficient and partial correlation coefficient between the original variables, and Bartley spherical test was performed at the significance level of 0.05.The results show that the N and P data sets meet the conditions for factor analysis.Based on the above work, we do factor analysis on the N and P data set, and use the principal component extraction method to get the principal component independent variables after dimensionality reduction.

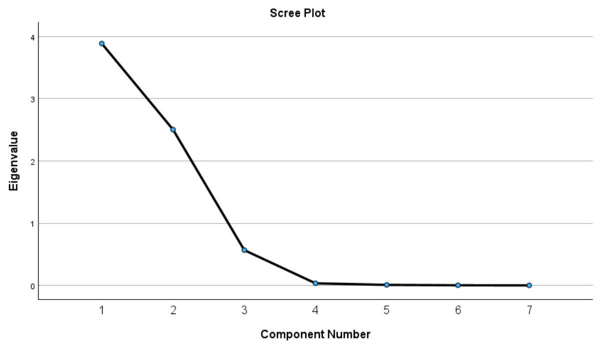

Figure 23: scree plot

As shown in the figure, through the above work, we found that it was more appropriate to reduce the dimensionality of the data set into three dimensions, and the cumulative contribution rate of the first three principal components was as high as 99.379%, which proved the rationality and feasibility of extracting the three principal components.Through the common factor variance graph, we find that these three common factors can almost reflect all the information of the independent variable.(Common factor variance diagram explanation: the common factor variance of the variable NH4 is 0.996, indicating that the contribution rate of the three common factors we extracted to the variance of the variable NH4 is 99.6%, that is, the three common factors can reflect the information of NH499.6%, and the rest are the same)

	initial	extraction
NH_4	1.000	.996
NO_3	1.000	.997
PO_4	1.000	.982
PP	1.000	.997
SS	1.000	.994
TN	1.000	.994
TP	1.000	.997

Table 4: Communalities

Then we use the Caesar normalized maximum variance method to rotate the initial factor load matrix to get the rotated factor load matrix (also known as the component matrix), which has the advantage of making the principal component easier to interpret.

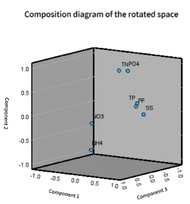

Figure 24: Scatter diagram

Rotated Component Matrix[a]

	Component 1	Component 2	Component 3
NH4	.135	-.633	.759
NO3	.285	-.034	.956
PO4	.317	.890	-.300
PP	.919	.285	.265
SS	.988	.101	.090
TN	.324	.942	.026
TP	.913	.340	.218

Figure 25: Factor load matrix

Then the component score coefficient matrix is obtained to quantify three principal components.

	component 1	component 2	component 3
NH_4	.017	-.189	.370
NO_3	-.247	.317	.790
PO_4	-.056	.416	-.003
PP	.340	-.055	-.027
SS	.549	-.319	.323
TN	-.227	.616	.339
TP	.334	-.033	-.045

Table 5: Component score coefficient matrix

The component score coefficient matrix intuitively shows the relationship between common factors and independent variables.

According to the composition matrix, we determined that the three principal components are pollutants, phosphorus and nitrogen.(Factor load matrix data diagram explanation: Factor load matrix is the correlation coefficient between variables and common factors. For example, the correlation coefficient between the first common factor and NH4 is 0.135. The larger the value, the more closely the variable is related to the common factor, that is, the common factor can better represent the variable, which is also the basis for what the three principal components represent respectively.)

At this point, the model preparation is basically complete.

5.3 Establishment of the model

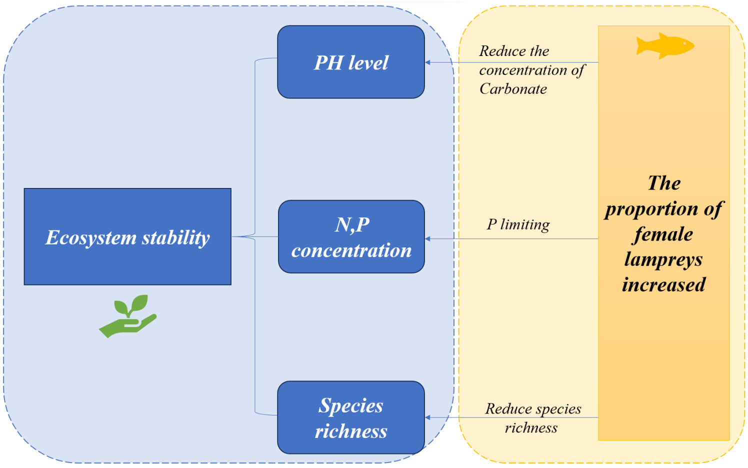

Figure 26: Algorithm flow chart

Combined with the principal component data obtained during the preparation of the above model, we used matlab, stata and other tools for fitting and regression, and established the regression model:

- Using different linear/nonlinear fitting models, we find that the SSE of Fourier equation is the smallest and the fitting effect is better under direct observation.Based on this, we found the relationship between the sex ratio of lampreys and the PH of the environment.

$$y = 8.3244 + 0.0019cos(xw) + 0.0155sin(xw) \tag{11}$$

$w = 0.1070$ and in the equation: y means PH and x means male proportion.

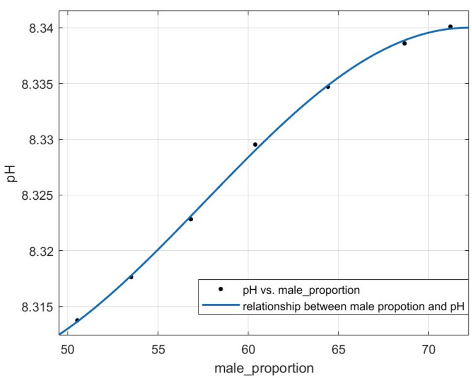

Figure 27: Relationship between sex ratio and PH

- Regression was performed using OLS standardized linear regression model.Based on this, we found the relationship between the sex ratio of lampreys and the three main components.

$$y_1 = -0.016x + 1.01 \quad and \quad y_2 = -0.116 + 6.89 \quad and \quad y_3 = 0.023x - 0.896 \tag{12}$$

y_1 y_2 y_3 are the three main components respectively.

In order to explore the relationship between ecosystem stability and indicators such as pH value, nitrogen-phosphorus concentration, and species richness, we applied the Analytic Hierarchy Process (AHP) method.

AHP is applicable to subjective and uncertain evaluation objects, and determines the importance of factors based on expert experience, which is very much in line with our evaluation object – ecosystem stability.

In order to analyze the influence of various factors on the stability of the lake ecosystem, we used the analytic hierarchy process to determine the species diversity, lake pH, pollutant content, nitrogen and phosphorus content to obtain the importance judgment matrix.

	richness	PH	pollutant	N	P
richness	1	6	2	3	3
PH	1/6	1	1/3	1/2	1/2
pollutant	1/2	3	1	1/2	1/2
N	1/3	2	1/2	1	1
P	1/3	2	1/2	1	1

Table 6

$$\begin{pmatrix} 1 & 6 & 2 & 3 & 3 \\ \frac{1}{6} & 1 & \frac{1}{3} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 3 & 1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{3} & 2 & \frac{1}{2} & 1 & 1 \\ \frac{1}{3} & 2 & \frac{1}{2} & 1 & 1 \end{pmatrix} \tag{13}$$

Let's first check the consistency of the matrix:

1.Computation consistency index CI

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{14}$$

2.Find the corresponding average random consistency indicator RI

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58	1.59

Table 7

3.Computed consistency ratio CR

$$\frac{CI}{RI} \tag{15}$$

It is concluded that CR=-0.079<0.1, and the consistency test is passed. Arithmetic average method, geometric average method and eigenvalue method are used respectively to calculate the weight and average value, and the weight of each factor with strong robustness is obtained.

The result of calculating the weight of the arithmetic mean is:[0.4637,0.0773,0.1652,0.1469,0.1469]

The result of geometric mean weight is:[0.4721,0.0787,0.1521,0.1486,0.1486]

The result of eigenvalue method is:[0.4609,0.0768,0.1669,0.1477,0.1477]

The result of the weights calculated by the three methods is:[0.4655,0.0776,0.1614,0.1477,0.1477]

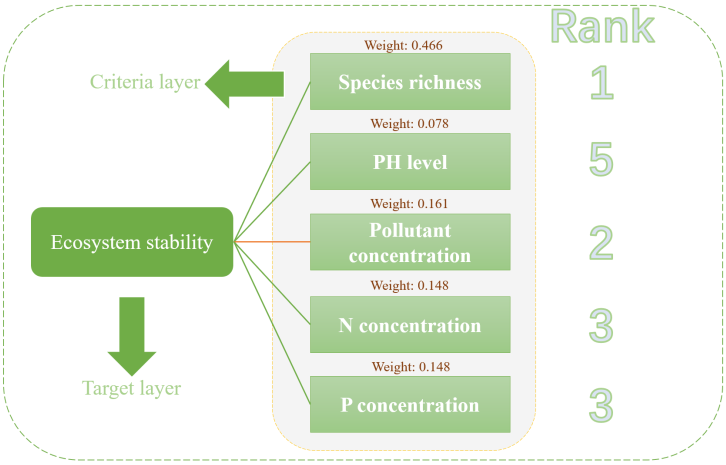

Figure 28: the process

The sex ratio of lampreys has an impact on the above criterion layer factors, and after the weight of criterion layer factors to ecosystem stability is determined, we can put forward targeted management recommendations.

So far, with these dependent variables as the intermediary, we completed the determination of the relationship between the sex ratio of lampreys and each dependent variable and the establishment of the model between the dependent variable and the ecosystem.Finally, we get the effect of the sex ratio of lampreys on the stability of their ecological environment.

5.4 Some analysis of result

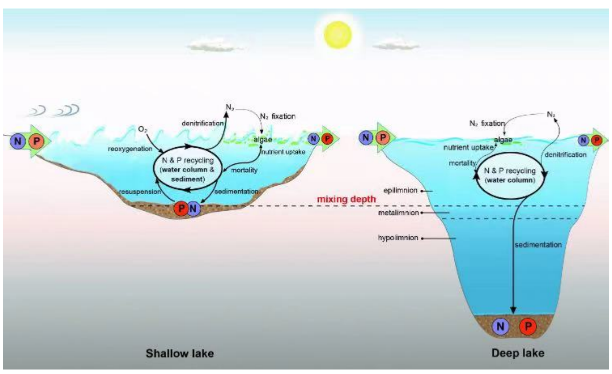

Figure 29: N P in shallow wake and deep wake

Schematic diagram of nitrogen and phosphorus geochemical cycles in lakes in shallow water (left) and deep water (right).In shallow lakes, the lake body is in a mixed state, nitrogen loss (denitrification) is strengthened, phosphorus loss (deposition) is weakened, and hydrodynamic disturbance promotes the release of phosphorus in the sediment, and eventually leads to a decrease in the ratio of nitrogen to phosphorus, which is often manifested as nitrogen restriction.However, in deep water lakes, generally only the lake mixed layer is active, nitrogen loss is reduced, and phosphorus sedimentation removal efficiency is improved, resulting in an increase in nitrogen to phosphorus ratio, which is mainly manifested as phosphorus limitation.Because Lake Superior is a deep water lake, the presence of lampreys exacerbates the phosphorus limit and makes a bigger impact.

6 Task4 :Parasite wave Model

To investigate whether an ecosystem with a variable sex ratio of lampreys population can provide an advantage to other species in the ecosystem, we analyzed a single parasite parasitic on lake trout and a parasite parasitic on lampreys.

6.1 Parasite 1

For the first parasite, we modeled the number of lake trout and the number of this parasite in a differential equation.

$$\begin{cases} \frac{\mathrm{d}x_1(t)}{\mathrm{d}t} = h_1 x_1(1-\eta_1\frac{x_2}{N2}-\frac{x_1}{N1}) & \\ \frac{\mathrm{d}x_3(t)}{\mathrm{d}t} = h_2 x_3(-1+\eta_2\frac{x_1}{N1}) & \eta_2\frac{x_1}{N1}<1 \\ \frac{\mathrm{d}x_3(t)}{\mathrm{d}t} = h_2 x_3(-1+\eta_2\frac{x_1}{N1}-\frac{x_3}{N_2}) & \eta_2\frac{x_1}{N1}>1 \end{cases} \tag{16}$$

η_1 means the nutrient absorbed by the fish per unit number of insects is the multiple of the nutrient consumed by the fish per unit number of insects and η_2 means the nutrient provided by a unit number of insects is the multiple of the nutrient consumed by a unit number of insects. N_1 means the maximum abundance of bass in initial environment and N_2 means the maximum abundance of paratise in initial environment. h_1 means the constant growth rate of bass and h_2 means the constant growth rate of paratise.

The population change curves of the two groups were obtained by assuming the parameters.

Combined with the above analysis of task 1 and the conclusion of classification model in task 2:The presence of lampreys has decimated lake trout populations and the female individual is longer and heavier.

It is reasonable to assume that females need more nutrients to grow and eat more lake trout.In other words, the higher the female proportion in lampreys, the greater the decline in lake trout.

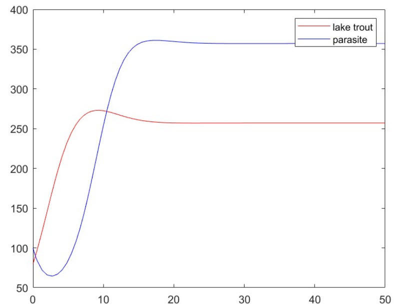

Figure 30: LAT and parasite

As we can see, parasite populations also drop dramatically.In addition, combined with the effect of the sex ratio of lampreys on ecosystem stability studied in the third question, we can see that the decline of ecosystem stability will put the species in the ecosystem at a disadvantage.So for this parasite, lampreys put it at a disadvantage.

6.2 Parasite 2

Due to the different feeding capacities of self-parasites in lampreys of different genders, the gender ratio of lampreys also affects the population of their own parasites. Through the Growth Model and Classifier Model in Task 2, we concluded that the biomass of female lampreys is greater than that of male lampreys, thereby providing stronger feeding capacity for parasites. It is reasonable to assume that the energy obtained by parasites parasitizing on lampreys is positively correlated with the biomass of lampreys. When the proportion of female lampreys is high, they have an advantage in terms of their own parasite population.

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7 Analysis on Model's Sensitivity

When considering the sex ratio of lampreys and ecosystem stability, and the effects of lampreys populations on other populations, the model results will be influenced by the lampreys' ability to access resources and by certain parameters in the ecosystem.Next, we will parameterize the cellular automata model that simulates the ecosystem to see if it can be generalized to describe the effects of lampreys on a range of variables in other ecosystems.

When the parameter setting is maintained as the original parameter setting in question 3, the areas of the three different regions tend to be stable with gradual accumulation of time, and the specific changes are as follows:

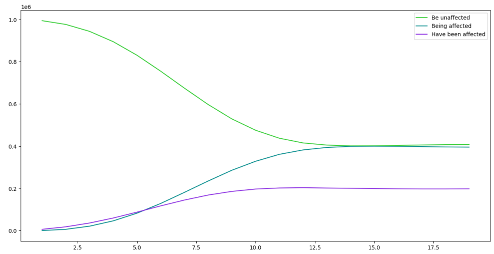

Figure 31: Regional area

Therefore, when we adjust the diffusion parameter, flow parameter and self-healing parameter, we need to compare the change of the stability value.Since the self-healing ability of the ecosystem in which lampreys population exists is not very different, here we only adjust the flow parameters affected by water velocity and the diffusion parameters affected by the amount of resources.

We adjusted the remaining parameters while fixing other parameters respectively, and finally obtained the following change results:

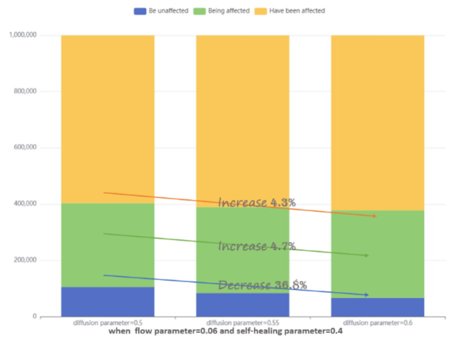

Figure 32: result 1

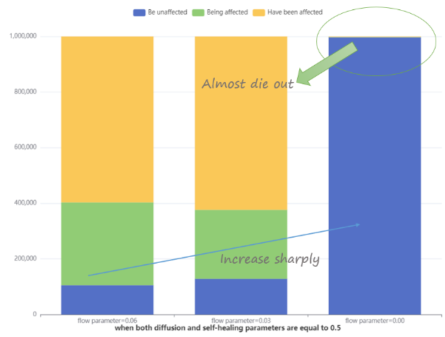

Figure 33: result 2

According to Figure 32, it can be seen that when the diffusion parameter increases, the simulated state of the unaffected region fluctuates greatly, indicating that the variable "unaffected region" in the simulation mechanism has a high sensitivity to the diffusion parameter.According to Figure 33, it can be seen that when the flow parameter decreases gradually, the overall simulation state is greatly affected. Within a limited time range, when the flow parameter is eliminated to 0, the entire simulation system is almost unaffected by lampreys, so we can conclude that the flow parameter has a great impact on the entire simulated ecosystem.

Based on the results of sensitivity analysis and the actual situation, we can analyze the reasonableness of setting river dam or intercepting lines to restrict the growth of lampreys when lampreys are flooding in the Great Lakes region, because after the establishment of restrictions, the flow parameters of the ecosystem will decrease, and the damage of the lampreys population to the stability of the ecosystem will decrease rapidly.

8 Strengths and Weaknesses

- Strengths:

1.The Lotka-Volterra predation model was extended and the anthropogenic fishing intensity parameters were introduced to show a more comprehensive and realistic ecological relationship.

2.The cellular automata model introduces the mechanism of river flow and ecosystem self-repair, and has strong simulation ability.

3.Soft-Voting classification decision model synthesizes various classification models, which is novel and robust at the same time.

- Weaknessess:

1.The establishment of the model is limited to the scope of lake ecosystem, and there may be a problem of insufficient generalization ability.

2.Due to the difficulty of data acquisition, parameters cannot be determined by fitting in part of the steps of model building, and the self-set parameters may be inconsistent with the reality.

9 Conclusion

According to our research, when the sex ratio is variable, the lamprey significantly impacts the population of its main prey, causing irreversible economic losses. At the same time, we have identified environmental factors such as temperature and resource availability. By using growth enzyme activity as an intermediary, we have determined the relationship between environmental factors and the individual growth rate of lampreys, and established the threshold boundaries for sex differentiation. In addition, we have studied the specific effects of the characteristics of lamprey population sex ratio changes on the ecosystem, including factors such as N and P concentrations, pH levels, and species richness. Finally, we have investigated the interaction between lamprey populations and other parasites, gaining a deeper understanding of interspecies relationships within the ecosystem. Through analysis, we have identified the advantages and disadvantages of lampreys changing their sex ratio based on resource availability. While this method helps lampreys adapt to the environment, it has negative implications for ecosystem stability. Based on all the models and analyses, we propose the following recommendations for managing the proliferating lamprey populations in the Great Lakes and other ecosystems:

- introduce harmless chemical substances to reduce the individual growth rate of lampreys, forcing a decrease in the proportion of female individuals and thereby limiting their reproductive rate.
- Address the impact of lamprey populations on water N and P concentrations by implementing nitrogen-phosphorus dual control or phosphorus control based on water depth to alleviate nitrogen or phosphorus limitations, preventing red tides or algal blooms and minimizing adverse effects.
- Establish interception zones or install river dams around lamprey habitats to restrict their range of activity and water flow, effectively controlling further damage to the ecosystem by lamprey populations.
- Introduce parasites that parasitize lamprey populations appropriately to limit the proportion of female individuals and reduce their reproductive rate.

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