Ecological Study of The Seven-Gill Eel Based on The Lotka-Volterra Model and Simulations

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Abstract. Seven-gill eels are migratory fish with a unique sex-determination mechanism, where the growth rate of juveniles determines the sex of adults. To explore the interactions of sevengill eels with the ecosystem, we first studied their habits and collected growth data. Then, we modelled the "marine-freshwater" migration of sevengill populations using a difference-in-differences approach and referring to the Lotka-Volterra model concept. In addition, we developed a model of "sevengill-prey" coexistence in the ocean through an intelligent body-based modelling approach and MATLAB simulations. The model incorporates factors such as human fishing, migration, stochastic events and interspecific competition, and is applicable to the same species.

Keywords: Lotka-Volterra model, intelligent body modelling, simulation simulation.

1. Introduction

Sex ratio is a key factor in population dynamics, with far-reaching effects on all aspects of biology. While the sex ratio of many species remains roughly balanced, external factors can cause it to fluctuate dramatically. An interesting example is the lamprey, an aquatic animal whose sex is determined by the growth rate of its larvae. When food is plentiful, lamprey larvae grow at an accelerated rate, thereby increasing the likelihood of developing into females. Conversely, limited food resources result in an increased likelihood of larvae developing into males.

To explore the effects of lamprey sex ratio on population dynamics and ecosystem. In this paper, we modeled the "ocean-freshwater" migration and "lamprey-prey" coexistence of lamprey populations, respectively. In the "ocean-freshwater" migration model, we described the behaviors of feeding, reproduction, migration, mortality and sex differentiation of lampreys, and also simulated and tested the ability of lampreys to resist external disturbances under different sex ratios and environmental conditions [1]. The model reveals the unique advantage of lampreys in changing sex for adaptation and reproduction, but this ability may lead to population extinction or ecosystem collapse.

In the "lamprey-fish" coexistence model, we simulated the growth environment of lampreys and calculated the probability of juveniles growing into females based on temperature and population sex ratio. The model describes the relationship between lampreys and other fishes, the relationship between lamprey population sex ratio, size and time, and further simulates population development under random events such as temperature changes, revealing the internal logic of lamprey reproduction.

Finally, to test the stability and applicability of the model, we simulated the effects of human expansion of fishing areas, increased fishing frequency, and greenhouse effect factors on fish populations.

2. "Marine-freshwater" migration patterns

Combining lamprey habits and available data, we developed an ecological cycle model. Using difference and iterative methods, we referenced the effects of sex ratio and available resources on lamprey populations and marine and riverine ecosystems through a series of calculations.

In this section, we will focus on how the number of adult lampreys of different sexes changes over time for a given larval birth sex ratio. We can vary the birth sex ratio of lamprey larvae and run

multiple simulations to compare and contrast the effects of different sex ratios on the environment and on the larvae themselves as they grow into adults.

In complex ecosystems infested with adult worms, adult populations are affected by a variety of factors. Here we mainly consider the effects of biological factors, and the effects of abiotic environmental factors are not considered for the time being. We categorize the biological factors affecting adult populations into the following three areas: food supply, larvae, and adults themselves.

2.1. Modeling

First, since adult lampreys in the ocean forage by parasitizing other marine fishes, the abundance of other marine fishes that serve as lamprey prey is closely related to the abundance of adult lampreys. First, because the marine ecosystem is relatively stable, we set the natural rate of growth of prey per unit of time to be constant R. We set the average amount of prey per lamprey per unit time as a constant i. We refer to the Lotka-Volterra equation and use an iterative method to derive the number of preys as a function of time $F(t)$ [2],

$$F(t+1) = F(t) + R \times F(t) - i(Ma(t) + Fe(t)) \tag{1}$$

$Ma(t)$is the number of adult male lampreys, and $Fe(t)$ is the number of adult female lampreys.

Secondly, the special reproduction and migration mechanisms of lampreys also have a decisive influence on the population size. Because some adult lampreys in the ocean migrate to rivers to spawn, the average proportion of adult lampreys migrating out of the ocean (to rivers to spawn) per unit time is a constant α. Because some adults die during migration, the average survival of adults during migration is a constant β.

Since all lampreys die after spawning, all adults that migrate from the ocean at the beginning die and are converted into organic matter that enters the ecosystem. Therefore, the total amount of organic matter produced throughout the process is the total amount of adult fish:

$$\alpha(Ma(t) + Fe(t)) \tag{2}$$

And the value of the number of adults that successfully migrate is:

$$\alpha\beta(Ma(t) + Fe(t)) \tag{3}$$

Furthermore, assuming that the average number of successfully grown larvae hatched from each adult female is constant λ then the number of new larvae is:

$$\lambda\alpha\beta Fe(t) \tag{4}$$

From the point of view of the larvae, the number of larvae will not only increase due to newborn larvae, but also decrease due to the outward migration of adults. We set the average rate of emigration of new adults (developed from newborn larvae) per unit time as a constant μ, so that the number of new adults migrating out at each moment in time is:

$$\mu Y(t) \tag{5}$$

From Equation (4)(5), it is clear that the function of larval population over time $Y(t)$ satisfies the requirement of the function of larval population over time:

$$Y(t+1) = Y(t) - \mu Y(t) + \lambda\alpha\beta Fe(t) \tag{6}$$

As for the migrating new adults, a portion of them die and are converted to organic matter during migration. The amount of this fraction is:

$$(1-\beta)\mu Y(t) \tag{7}$$

The remaining portion of the larvae migrate successfully to the ocean. The number of this fraction is:

$$\beta\mu Y(t) \tag{8}$$

As for the death of adult lamprey in the sea, assuming that the coefficient of natural mortality of adult lamprey related to the competition of its own population is p, together with the fact that the lamprey is a parasitic organism, its natural mortality rate is negatively correlated with the number of prey populations, therefore, we constructed the inverse proportionality function, i.e., when all the fish in the sea are dead, the natural mortality rate of the lamprey will reach positive infinity, i.e., all of them will die, and if there are enough fish in the sea, the natural mortality rate of the lamprey will be almost zero due to the parasitism. parasitism, the natural mortality rate of lampreys is almost 0. If there are enough fish in the sea, the natural mortality rate of lampreys is almost zero due to parasitism, where the coefficient related to the prey population size is I. The number of adult lampreys killed per unit time can be found as:

$$\frac{p(Fe(t)+Ma(t))}{I\times F(t)} \tag{9}$$

Finally, we set the proportion of males in the new adult population to be $m(t)$ and the proportion of females as $f(t)$. Combining Equation (2)(8)(9) gives the following function of the number of adult males over time:

$$Ma(t+1) = Ma(t) + \mu\beta m(t)Y(t) - \alpha Ma(t) - \frac{pMa(t)}{I\times F(t)} \tag{10}$$

Similarly, the number of adult females as a function of time was satisfied:

$$Fe(t+1) = Fe(t) + \mu\beta f(t)Y(t) - \alpha Fe(t) - \frac{pFe(t)}{I\times F(t)} \tag{11}$$

On the other hand, total organic matter is given by Equation (2)(7):

$$E = \sum_{t=0}^{n} (\alpha(Ma(t) + Fe(t)) + (1-\beta)\mu Y(t)) \tag{12}$$

By constructing the above model, we can simulate the interrelationships between larvae $Y(t)$, adult lamprey, and the fish population under the same $m(0)$ sex-birth ratio, and we can also calculate the amount of additional organic matter accumulation in the river ecosystem at a given time t.

2.2. Ecosystem effects of lamprey sex ratio

According to literature, the impact of lampreys on the broader ecosystem is twofold. Firstly, their dead bodies contribute nutrients to river and marine ecosystems, particularly rivers during the spawning period when they enter rivers to spawn and die from exhaustion afterwards. Secondly, they harm marine fish as adult lampreys parasitize large fish and feed on their blood, leading to infections and death in these fish. A single lamprey can kill one fish [3]. Model 1 established in the research illustrates the relationship between lampreys, parasitized fish, and hatchlings under certain initial gender ratios. The model shows that at time t, the quantity 'E' represents the additional organic matter provided to the river ecosystem by lampreys (due to predation and post-spawning death), and ' F ' indicates the change in fish population in the sea under extremely low natural growth rates. By varying the initial gender ratio $m(0)$, the study investigates the impact of different values on the quantity of organic matter ' E ' and the fish population ' F ', demonstrating the effect of lampreys' gender adjustment ability on the larger ecosystem, especially river ecosystems.

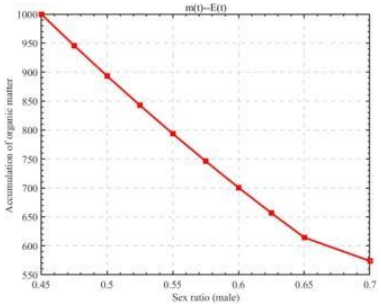

Fig. 1 Effect of sex ratio on organic matter

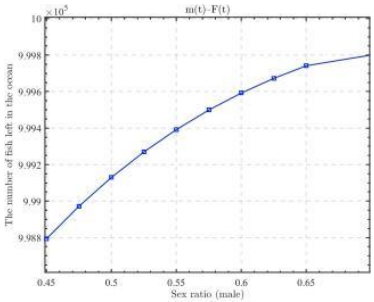

Fig. 2 Impact of sex ratio on marine fish species

According to Fig. 1 as the proportion of males decreases, the amount of organic matter provided to nature increases. This favors nutrient cycling and biodiversity in the ecosystem. It also contributes to soil health by helping to maintain soil structure and soil moisture retention.

Subsequently, we focus on the quantity of fish in the sea. We set the initial gender ratio variable $m(0)$ similarly between 0.45-0.70, increasing in steps of 0.025, and calculate the amount of ' F ' at t=13 for each scenario. Given the abundance of fish in the sea [4], we study the changes in their quantity over a longer period of time and plot the results as shown in Fig. 2.

According to the results shown in Fig. 2, as the proportion of males decreases, the number of fish remaining in the sea also decreases.t=13 The decrease in the number of fish at $m(0)$=0.5 The decrease of fish at is $m(0)$=0.6. This will damage the local fishery and may even disrupt the original food chain in the area, causing major damage to the ecosystem.

From these experiments on the two variables, we conclude that a lower initial male ratio indicates a trend of population growth and expansion. This further impacts the environment, leading to more accumulation of organic matter over the same time period, more widespread and severe parasitism on marine fish, and possibly a reduction in fish numbers, causing ecological damage.

2.3. Impact of natural disasters on gender ratio

For marine disasters, we created a T=9 iteration, assuming that the lamprey population suddenly decreases to 20% There is no change in the number of lampreys in T=5, while the number of other fish in the ocean remains unchanged. Faced with a sudden drop in population, lampreys passively increase the proportion of females. This is because, despite the sharp decline in lamprey populations, there is no significant decrease in the number of other fish, their food source, resulting in more food and faster development per lamprey, which increases the proportion of females.

For the river disaster, we created a T=9 iteration, assuming that lamprey larvae in the river suddenly decrease to 20% the time when the number of lamprey larvae in the river T=5, while the number of other fish in the ocean remains constant. The proportion of lanternfish females will similarly increase due to the availability of more food.

The results under both disasters are shown in Fig. 3.

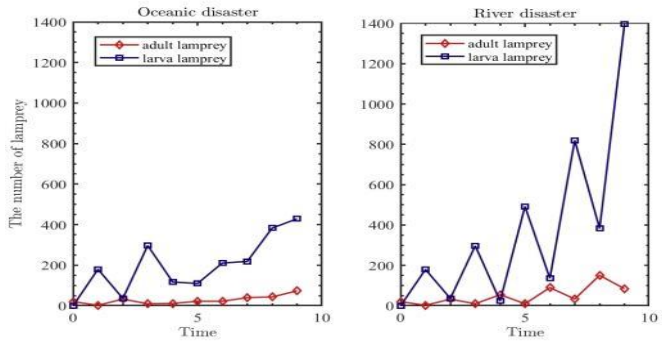

Fig. 3 Effects of natural disasters on lamprey populations

Based on the results shown in Fig. 3, the Year 5 catastrophe reduced lamprey adult and juvenile populations to 20% levels, but the lamprey population only needed 2–3-time units to recover to its original state. This indicates that the lamprey population is highly reproductive. m=0.5 The high reproductive capacity of the lamprey population suggests that if the species can adjust its sex in times of crisis, it can effectively respond to disasters. It is clear from the figure that although the lamprey population fluctuates significantly, the overall trend is one of recovery and expansion.

The unique reproductive strategy of lampreys, with larvae spawning in rivers and adults growing in the ocean, coupled with their unique ability to change sex, allows them to recover from disasters in both rivers and oceans, especially when the proportion of males is low. This makes lampreys highly resistant to changes in external environmental factors and plays a positive role in expanding populations and protecting them in the face of major disasters [5].

Comparing the two scenarios, marine hazards have a greater impact on lampreys than river hazards, which only reduce larval populations. Human intervention is less effective, and efforts to control lampreys have been largely ineffective, as seen in the U.S. Great Lakes. Lamprey populations are resilient and difficult to eradicate unless both marine and riverine disasters occur simultaneously, which is highly unlikely.

3. "Lamprey-fish" coexistence model

3.1. Description of variables

To simplify the discussion of prey below, we refer to the previously mentioned prey as "fish". Fish have a growth level L between 0 and 10. L greater than or equal to 5 is referred to as "adult/large fish", otherwise it is referred to as "juvenile/small fish". If L exceeds 10 during the calculation, it is set to 10.

Position P is a binary ordered pair containing information about two directions, denoted as (x, y) , where y represents the depth. The portion within is called the "shallow sea". [0,100] *[0,10] The portion within is called the "shallow sea". When a lamprey successfully parasitizes a fish, it stays in the same position as the fish.

Growth rate V The range is [0,1]. With the L decreasing and E increase, V then the growth rate increases. Assuming they have the same effect, if $V(t)$ is less than 0, it is set to 0.01. In other cases:

$$V(t) = \frac{E}{100} - \frac{L}{10} \tag{13}$$

Energy values for fish or lampreys range from [0, 100]. Initially, all lampreys and fish have energy equal to 10 times their initial growth level. Organisms need to consume energy to survive, and per unit of time, lampreys and fish with a growth level of L need to consume energy equal to their own value of $(L + 1)/2$ of its own value. Lanternfish can only obtain energy through. They can only obtain energy through parasitism. Fish can obtain energy by taking energy from the ocean and feeding on lanternfish per unit time. When energy is less than or equal to 0, the fish/lamprey will die.

Gender S Indicated by 0 and 1, where 0 is female and 1 is male.

RH is the predation radius of the lamprey or fish. Consider that the predatory capacity of fish varies with their level of growth, RH Determine the following $RH = L + 1$ as L In the case of [0,5]; $RH = 6$ for L in [5,7]; $RH = 13 - L$ for L in [7,10].

3.2. Modeling

Parasitic and predatory relationships exist between lampreys and fish in the observation area. Over time, lampreys and fish undergo natural processes such as reproduction and mortality. Therefore, we define the following behaviors to describe population dynamics in the ocean.

Growth Behavior: Growth Levels of Lampreys/Fish over Time t to t+1 growth is shown below:

$$L(t + 1) = L(t) + V(t) \tag{14}$$

Predation behavior: Any fish can prey on lampreys. The probability of success of a fish to prey on lampreys takes into account its growth level and energy. Index "1" represents lampreys and index "2" represents fish. The probability of success of fish predation on lampreys is expressed as p_1:

$$p_1 = \left(\left(10 - |L_2 - 5| + \frac{E_{n2}}{10}\right)\right) \div \left(\left(10 - |L_2 - 5| + \frac{E_{n2}}{10}\right) + \left(10 - |L_1 - 5| + \frac{E_{n1}}{10}\right)\right) \tag{15}$$

Since predation consumes energy and some of the residual energy is converted to organic matter, when a fish succeeds in feeding on a lamprey, it gains 0% of the lamprey's current energy and the energy of the prey becomes 0%. 50% of the lamprey's current energy, while the energy of the preyed upon lamprey becomes 0.

Move Behavior: the lanternfish or fish moves after 1 unit of time to any point within a circle centered on its current position and with a radius of R is any point within a circle of radius.

Female lampreys with mature spawning behavior have some probability of leaving the area to spawn. They will not return to the study area. The probability of a female lamprey leaving the area to spawn increases with her growth level (L). The probability of a female lamprey leaving the area to spawn is $L/50$. lampreys that leave the spawning area are considered dead and their data will be deleted.

Parasitic behavior: Any lamprey can parasitize fish. The probability of success of a lamprey parasitizing a fish takes into account its growth level and energy. Index "1" represents lampreys and index "2" represents fish. The probability of success of lamprey parasitizing fish is expressed as p_2 :

$$p_2 = \left(\left(10 - |L_1 - 5| + \frac{E_{n1}}{10}\right)\right) \div \left(\left(10 - |L_2 - 5| + \frac{E_{n2}}{10}\right) + \left(10 - |L_1 - 5| + \frac{E_{n1}}{10}\right)\right) \quad (16)$$

When a lamprey successfully parasitizes a fish, it moves with the parasitized fish. It gains per unit of time 5% of energy to the parasitized fish, while the parasitized fish's energy is reduced by 5% of its current energy. If the current energy of the parasitized fish is less than the energy of the 10% the energy of the lamprey, the lamprey gains all of the energy of the parasitized fish, and the energy of the parasitized fish becomes zero.

3.3. Simulation results and analysis

Based on the above model, we wrote a program in MATLAB and obtained the following results [6], i.e., time (t) plotted against the number of lampreys, small and large fish, and the sex ratio of lampreys.

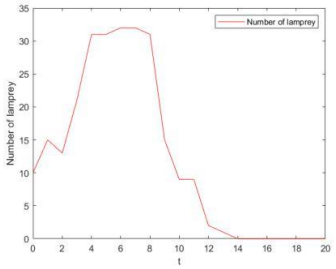

Fig. 4 Lamprey abundance over time

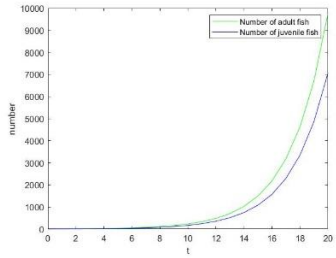

Fig. 5 Number of small and large fish over time

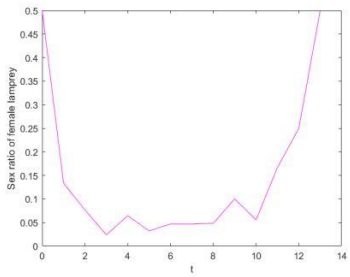

Fig. 6 Sex ratio of lampreys over time

As can be seen in Fig. 4, Fig.5, and Fig. 6 above, the sex ratio of lampreys remains relatively stable over time, even as more lampreys and fish migrate into the ocean.

The analysis suggests that changes in lamprey abundance and sex ratios may affect overall population dynamics. Reductions in the number of female lampreys may affect their reproductive success and ultimately the population as a whole. Changes in sex ratios may also affect ecosystem stability. Excessive numbers of lampreys or imbalances in sex distribution may lead to increased competition for resources and pose a threat to ecosystem stability.

This adaptation can help lamprey populations to better utilize environmental resources, increase numbers, and enhance fitness. Adjusting sex ratios can be beneficial in maintaining the reproductive

capacity of the population. Increasing the proportion of females is advantageous when resources are scarce. This adaptive strategy makes lamprey populations more flexible and better able to cope with environmental stress and resource scarcity.

Imbalanced sex ratios can easily lead to inbreeding, which reduces the genetic diversity of populations. Large fluctuations in lamprey sex ratios can also affect the populations of other species that feed on lampreys. Rapid changes in sex ratios can disrupt the existing dynamic equilibrium of a population, and it takes time and resources to re-establish the balance.

4. Ecosystem impacts of changes in lamprey sex ratios

4.1. Modeling

To investigate whether changes in the sex ratio of lamprey populations in an ecosystem give an advantage to other organisms in the ecosystem, we introduced the effect of parasites. We hypothesized that, within each time step, a parasite randomly attaches to any fish with a probability of 0.05, resulting in a natural decrease in that fish's energy per unit of time from that moment onward 20% of energy.

When introducing lanternfish into the observation area from the outside, we no longer fixed the sex ratio of male and female lanternfish at 0.5. Instead, we included a temperature factor in the model.

We add: the probability that a juvenile lamprey is a male during generation (p_3) is related to the time that the lamprey is at the $t(Im\ (t))$ and current temperature $T(t)$. It is calculated as:

$$p_3 = 0.8 \times (1 - \exp\{1 - \mathrm{Im}\ (t)\}) \times (1 - \exp\{-\mathrm{sqrt}\ (T(t) - Tb\ |)\}) \tag{17}$$

where Tb represents the temperature best suited for female lampreys, and the temperature $T(t)$ fluctuates around.

$$T(t) = Tb + 3\sin\ (t) \tag{18}$$

4.2. Simulation results and analysis

Based on the model for assessing the effect of lamprey sex ratio on ecosystem stability and considering the effects of parasites and temperature while other basic conditions remained constant, we conducted an analysis in MATLAB, which yielded the following results.

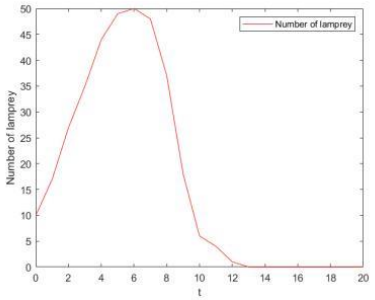

Fig. 7 Lamprey abundance over time

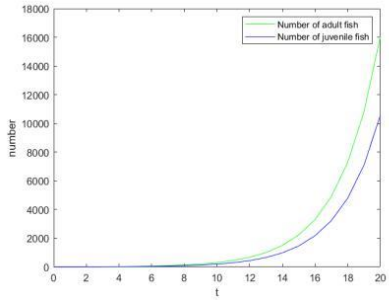

Fig. 8 Numbers of small and large fish over time

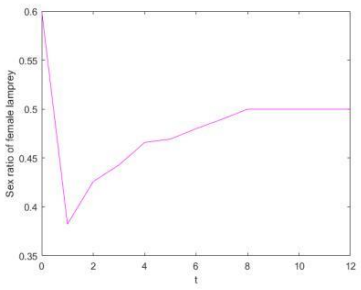

Fig. 9 Sex ratio of lampreys over time

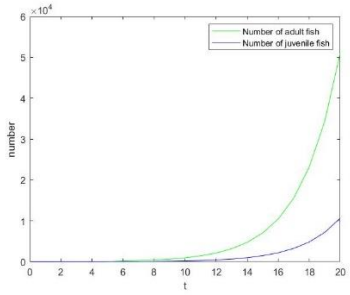

Fig. 10 Numbers of small and large fish over time

In addition, we introduced 100 lampreys and large fish to the marsh and obtained information on the dynamics of fish populations over time.

As can be seen from Fig. 7, Fig. 8, Fig. 9 and Fig. 10, the ratio of large to small fish increased significantly over time after the introduction of 100 lampreys and walleye.

4.3. Analysis of simulation results

The variability in lamprey gender ratios in response to external environmental factors may bring several advantages to other organisms in the ecosystem, particularly parasites:

1. Diverse Parasitic Strategies: Lamprey gender ratio fluctuations can increase the diversity of parasitic strategies employed by parasites. In environments where the male lamprey ratio is higher, parasites may preferentially parasitize male lampreys, as males might be more accessible or vulnerable. Conversely, in environments with a higher female lamprey ratio, parasites may need to adjust their parasitic strategies to adapt to female lampreys.

2. Improved Parasitic Success: Changes in lamprey gender ratios can directly impact the success rate of parasites. For example, if male lampreys are more susceptible to a particular type of parasite, in environments with a higher male ratio, that parasite's success rate may increase.

3. Adaptation to Environmental Changes: The variability in lamprey gender ratios is a direct response to environmental changes. Parasites that can adapt to these changes may have a better chance of surviving and reproducing in evolving environments. For instance, if parasites can quickly adapt to an increase in the male ratio, they may thrive and reproduce more effectively in such environments.

4. Ecosystem Stability: Lampreys are a part of the ecosystem, and changes in their gender ratios may impact the stability of the entire ecosystem. Parasites, being another integral component of the ecosystem, could benefit from this stability, as a stable ecosystem may provide them with more opportunities for survival and reproduction.

5. Stability and sensitivity analysis of the model

In order to verify the stability and applicability of the model in the presence of disturbances, we carried out the following design. At t=5 time, the human fishing area in the region expands and the shallow sea area changes from y= [0,10] changed to y= [0,20] The probability of fishing increases to q=0.3. A new simulation is then performed.

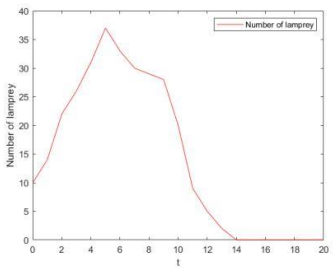

Fig. 11 Lamprey abundance over time

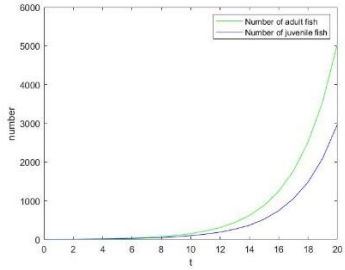

Fig. 12 Numbers of small and large fish over time

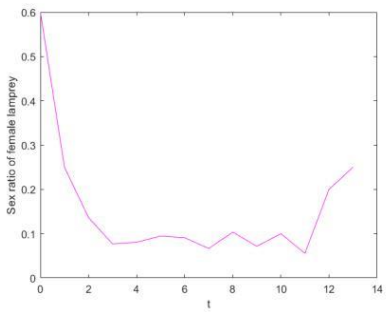

Fig. 13 Sex ratio of lampreys over time

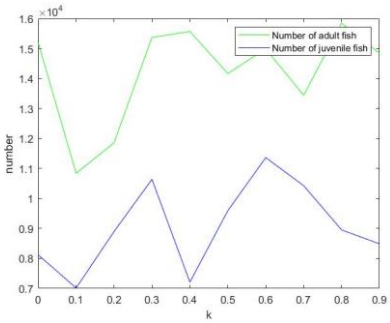

Fig. 14 Number of small and large fish versus k-value

Since the greenhouse effect has led to an increase in ocean temperatures, making the growing conditions for lampreys increasingly unfavorable, we have modified the migration process as follows:

Instead of generating young lampreys as " $5 \times (1 + Im\ (t + 1 - 10)$ rounded down," we now generate young lampreys as "$5 \times (1 + Im\ (t + 1 - 10)$" rounded down," where k is in the range [0,1]. We keep other conditions unchanged and maintain a fixed maximum runtime (tmax). We will now plot the graphs depicting the relationships between k and the final quantities of lampreys, small fish, large fish, and the gender ratio of lampreys, and compare them to the previous scenario.

As can be seen from Fig. 11, Fig. 12, Fig. 13 and Fig. 14, the comprehensive analysis of the simulation experiments showed that the populations in the marine ecosystem could remain relatively stable in terms of numbers and sex ratios when perturbations were imposed, such as changing the proportionality coefficients of the reproduction rate and total number of large/small fishes per unit of time or increasing the intensity of fishing and the area fished. This indicates that the model shows good stability under various disturbances and environmental changes.

6. Conclusion

Based on our model, the life habits of lampreys, an organism with a unique sex-determining mechanism, and its interaction with the ecological environment are preliminarily demonstrated. As we reveal in the paper, on the one hand, this unique sex-determining mechanism helps to maintain the prosperity of lamprey species under certain environmental fluctuations; on the other hand, under certain conditions, this mechanism can also maintain the prosperity of other organisms' populations and even the overall stability of the ecosystem. Our study of lampreys has some generalizability, and for other organisms with sex-determining mechanisms, we can construct similar "marine-freshwater" migration models and "lamprey-fish" symbiosis models to study the impact of these organisms on the environment. Humans can make full use of this natural law to realize their own development while maintaining ecological stability, and ultimately achieve the goal of harmonious symbiosis with nature.

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