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Ecological Impacts of Lamprey Based on Lotka-Volterra Model

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Abstract. Unlike most organisms, lampreys have a unique ability to change their sex based on the status of environmental resources. This study aims to investigate the intrinsic relationships between species within an ecosystem and to assess the advantages and disadvantages of lampreys' ability to change sex. A Gender Determination Model was established to represent the interaction between lamprey populations and the environment. This article used three evaluation criteria, including the impact on environmental conditions, performance in interspecies competition, and the Shannon-Wiener index. The Dynamic Model of Lamprey and Parasite populations was developed to explore the impact of the lamprey's sex change mechanism on parasites within the ecosystem. by adjusting parameters to represent different parasitic states, by comparing situations with and without lamprey gender transformation mechanisms. We drawn the conclusion that, regardless of the type of parasite, none gained an advantage when lampreys had gender transformation mechanisms. Finally, this article obtained the sensitivity analysis curves for population size and environmental condition in MATLAB. This article elucidates the intricate interplay between the sex determination mechanism of lampreys and environmental resources, offering a novel perspective on the role of sexual plasticity within ecosystems. Particularly against the backdrop of increasing human activities that impact the natural ecological balance, understanding these interactions can facilitate more effective conservation and management of species that rely on specific sex ratios or particular population dynamics.

Keywords: Lampreys; Lotka-Volterra Model; Differential Equations.

1. Introduction

Lamprey has a recorded history of 360 million years, spanning several mass extinction, while its morphology seems to have changed little, and it is known as a "living fossil" [1]. Because of the cooler water temperatures required for larval growth, today they are mostly found in freshwater and coastal waters in temperate and cold zones of the northern and southern hemispheres [2]. In natural environments, the sex ratio of lampreys is not fixed but varies due to external environmental factors. The growth rate during their larval stage determines whether they become male or female, and this growth rate is influenced by environmental constraints such as food resources. In environments with scarce resources, male lampreys may constitute a larger proportion, while in environments with abundant food, female survival is favored. This ability allows lampreys to adjust their sex ratio according to environmental conditions, adapting to different survival pressures. However, global warming has worsened the preservation of lampreys because of the destruction and/or deterioration of their habitats caused by the construction of dams, environmental contamination, water extraction, manipulation of river currents, and excessive fishing practices [3]. Urgently needed are high-quality data on commercial catches and mitigation efforts' effectiveness, such as habitat restoration and fishing rules. Engaging the public and stakeholders in lamprey conservation is key to safeguarding their ecological and cultural significance and raising awareness of their vulnerability [4].

Many studies indicate that lampreys are invasive species that can have negative impacts on local ecosystems. Robinson [5] et al. estimated lamprey populations in locations such as Lake Superior and Lake Michigan by dividing the captured individuals by assumed capture efficiencies. There have been studies on who lampreys in the sea are influenced by and which organisms they may affect. For example, Coble [6] et al. found that the sharp decline in trout populations in Lake Michigan and Lake Huron is primarily attributed to lamprey predation. Several studies demonstrate the lamprey's resilience, as even after implementing multiple control plans, they still have the potential to rebound. However, current research on modeling the effects of lampreys on other organisms in ecosystems and how their gender-changing ability influences these organisms is scarce. This paper will focus on this aspect by establishing dynamic models to simulate interactions between lampreys and other organisms. This paper will investigate the establishment of a dynamic model. This article will study the impact of lampreys on the ecosystem and how the effects of lampreys on the ecosystem, in turn, affect themselves. A comparative analysis will be conducted between scenarios with and without sex change mechanisms. Finally, this article will expand the model to include multiple populations and explore how the sex change in lampreys affects parasites within the ecosystem. This analysis requires a comprehensive observation of the dynamic changes in both lamprey and parasite populations to assess the impact of lampreys on parasites.

2. The advantages and disadvantages of the gender-changing

2.1. The model of gender-environment interaction

To investigate the impact of gender-changing in the lamprey population on its advantages and disadvantages, this article constructed a gender determination model. This article explored the interaction between population size and environmental conditions. Additionally, this article examined intraspecific competition, investigating resource utilization efficiency and competition indices. This article also assessed whether obtaining a greater advantage within competitive relationships is possible.

Initially, this article established a population dynamic model [7]:

$$N(t) = N(t-1) + r(t)N(t-1)\left(1 - \frac{N(t-1)}{K}\right) \tag{1}$$

Where K represents the environmental carrying capacity, this article established a dynamic model for environmental conditions:

$$E(t) = \max\{0, \varepsilon(E_{\max} - E(t-1) + E(t-1) - \delta N(t-1))\} \tag{2}$$

Where ε represents the environmental regeneration rate, and δ is the population's consumption rate of the environment. Based on actual circumstances, this article set a standard threshold for the environment denoted as E_s. This article introduced a factor, e_g, e_b to assess the quality of the environment. This article assumed a linear relationship between environmental conditions and the gender conversion rate. When the environmental conditions exceed the threshold, e_g increases from 0. When the environmental conditions fall below the threshold, e_b so increases from 0.

$$\begin{aligned} &if\ E(t-1) \geqslant E_s, \begin{cases} e_g = m_1(E(t-1) - E_s) \\ e_b = 0 \end{cases} \\ &if\ E(t-1) < E_s, \begin{cases} e_g = 0 \\ e_b = m_2(E_s - E(t-1)) \end{cases} \end{aligned} \tag{3}$$

This article define p_f and p_m as the probabilities of differentiating into females and males, respectively.

$$\begin{cases} p_f = sigmoid(\gamma_{\max} \cdot e_g \cdot E(t-1)) \\ p_m = sigmoid(\gamma_{\max} \cdot e_b \cdot E(t-1)) \end{cases}, \quad sigmoid(x) = \frac{1}{1+e^{-x}} \tag{4}$$

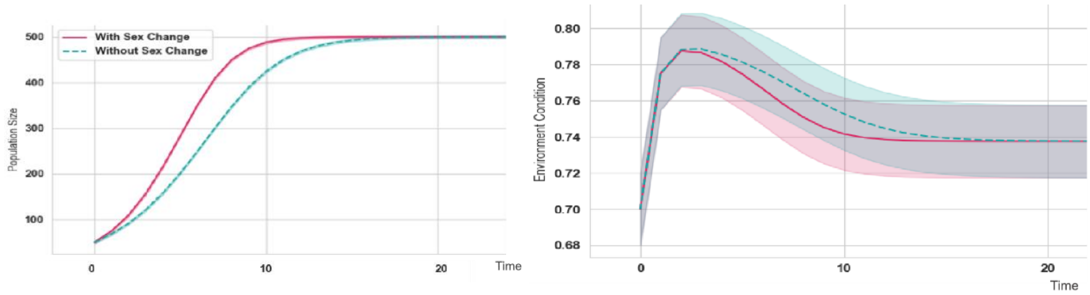
Where m_1, m_2 is the coefficient representing the impact of environmental conditions on the environment factor, and $\gamma_{\max}$ is the maximum value influencing the probability of gender transformation. Based on this, this article define the growth rate as follows:

$$r(t) = r_0 + \alpha_0 p_f(t) - \beta_0 p_m(t) \tag{5}$$

Where α_0, β_0 are the coefficients representing the impact of the environment on the probability of gender transformation for females and males, respectively. Additionally, this article establish a lamprey population model where gender does not change with environmental variations.

In this model, the growth rate remains constant over time.

$$N_2(t) = N_2(t-1) + r_1 \cdot N_2(t-1)\left(1 - \frac{N_2(t-1)}{K}\right) \tag{6}$$



(a) the Population of Lampreys (b) Environmental Conditions

Figure 1. Changes in the Population of Lampreys with Environmental Conditions

The figure 1 shows that the lamprey population with gender changes initially has a greater advantage in interacting with the environment compared to the population with constant gender. This advantage is manifested in a faster population growth rate, but over time, this advantage gradually diminishes. The second graph indicates that the lamprey population with gender changes consumes more under varying environmental conditions, and as time progresses, this difference gradually narrows. The reason behind this lies in the fact that the growth rate of the lamprey population is more closely tied to environmental changes, maximizing the utilization of environmental resources and consequently leading to relatively greater environmental consumption.

2.2. Population competition

In the context of population competition, this article discuss the competitiveness of male and female lampreys separately This article assume that the growth rates of lamprey females and males satisfy the following relationships:

$$\begin{cases} r_f = r_0 + \alpha_0 p_f(t) \\ r_m = r_0 - \beta_0 p_m(t) \end{cases} \tag{7}$$

In order to compare the advantages and disadvantages of lampreys with sex ratios that can change with the environment and lampreys with sex ratios that do not change with the environment, this article establish the following model:

$$\begin{cases} \dfrac{dN_f}{dt} = r_f N_f \left(1 - \dfrac{N_f + N_m}{K} - \sigma_1 \dfrac{P}{K_P} - \sigma_2 \dfrac{Q}{K_Q} - \sigma_3 \dfrac{F}{K_F} - \sigma_4 \dfrac{G}{K_G}\right) \\ \dfrac{dN_f}{dt} = r_m N_m \left(1 - \dfrac{N_f + N_m}{K} - \sigma_5 \dfrac{P}{K_P} - \sigma_6 \dfrac{Q}{K_Q} - \sigma_7 \dfrac{F}{K_F} - \sigma_8 \dfrac{G}{K_G}\right) \\ \dfrac{dP}{dt} = r_P N_P \left(1 - \dfrac{P}{K_P} - \sigma_9 \dfrac{N_f + N_m}{K} - \sigma_{10} \dfrac{Q}{K_Q} - \sigma_{11} \dfrac{F}{K_F} - \sigma_{12} \dfrac{G}{K_G}\right) \\ \dfrac{dQ}{dt} = r_Q N_Q \left(1 - \dfrac{Q}{K_P} - \sigma_{13} \dfrac{N_f + N_m}{K} - \sigma_{14} \dfrac{P}{K_P} - \sigma_{15} \dfrac{F}{K_F} - \sigma_{16} \dfrac{G}{K_G}\right) \\ \dfrac{dF}{dt} = r_F N_F \left(1 - \dfrac{F}{K_F} - \sigma_{17} \dfrac{N_f + N_m}{K} - \sigma_{18} \dfrac{P}{K_P} - \sigma_{19} \dfrac{Q}{K_Q} - \sigma_{20} \dfrac{G}{K_G}\right) \\ \dfrac{dG}{dt} = r_G N_G \left(1 - \dfrac{G}{K_G} - \sigma_{21} \dfrac{N_f + N_m}{K} - \sigma_{22} \dfrac{P}{K_P} - \sigma_{23} \dfrac{Q}{K_Q} - \sigma_{24} \dfrac{F}{K_F}\right) \end{cases} \tag{8}$$

To more comprehensively simulate the potential impact of lampreys on other species, this article set up five species including lampreys, denoted by A,B,C,D,E, where A represents lampreys. This article will specifically analyze the changes in the numbers of male and female lampreys, and then combine the weakening effect of resource consumption on the growth rate of marine organisms, as well as the different changes in the growth rates of male and female lampreys due to the influence of environmental conditions.

In the above model equation, P,Q,F,G respectively represent the quantities of the four species other than lampreys. $\sigma_i (1 \leqslant i \leqslant 4)$ respectively represent the multiples by which unit quantity of species A consumes the food supplied to female lampreys and unit quantity of female lampreys consumes the food supplied to lampreys, assuming both are less than 1, similarly for other $\sigma_i (5 \leqslant i \leqslant 24)$. r_P, r_Q, r_F, r_G respectively represents the natural growth rate of P,Q,F,G. To better approximate the real ecological environment, this article assume that the natural growth rates of the species decrease with the decrease of environmental resources [8].

Through parameter settings that distinguish between different species, figure 2 illustrate the impact of changes in the sex ratio of lamprey populations under the influence of other species, regardless of environmental effects. When lampreys can respond to environmental changes by altering their sex, as the marine biomass continues to increase and environmental resources diminish, the growth rate of male lampreys exceeds that of females. Even facing competition for resources from other species, male lampreys can still maintain continuous growth. In this scenario, male lampreys have an advantage in the ecological environment. Although the growth rate of female lampreys declines during the competition for resources, overall, due to the stronger competitive ability of male lampreys, the competitiveness of the entire lamprey population is higher than when the sex ratio remains unchanged.

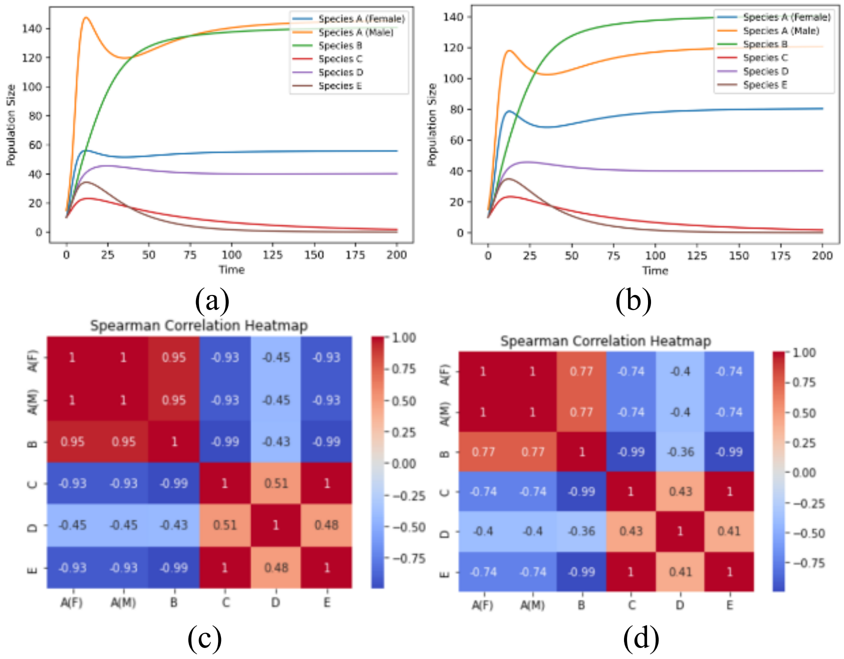


Figure 2. The population dynamics graphs of lampreys with changing gender ratios and lampreys with constant gender ratios

On the other hand, when lampreys do not change sex in response to environmental changes, both males and females do not have an advantage in the overall ecological environment and face competition from other species.

Then, this article consider the impact of the Shannon-Wiener index, and competition index on the population.

The competition index [9] is the average of the product of individual functional traits and competition abilities. It is utilized to quantify the overall efficiency of individuals in terms of resource acquisition and competition:

$$CI = \frac{\sum(FT \times CA)}{N} \tag{9}$$

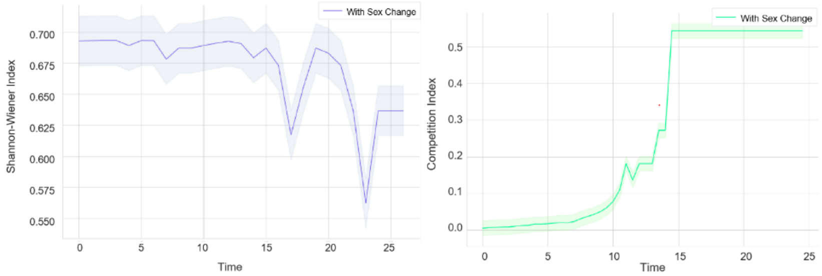
Where N represents the total number of individuals in the species.

The Shannon-Wiener Index is a commonly used metric for describing species diversity in an ecosystem [10]. It comprehensively considers both species richness and evenness, providing a more comprehensive measure of species composition in an ecosystem. The formula for calculating the Shannon-Wiener Index is as follows:

$$H = -\sum_{i=1}^{S} p_i \ln(p_i) \tag{10}$$

Where S is the number of species in the ecosystem, and p_i is the relative abundance of the i-th species.

This article have plotted the temporal changes in resource utilization efficiency and competition index for a lamprey population with changing gender functionality. Additionally, this article have depicted the dynamic changes in the Shannon-Wiener Index over time for the ecosystem where the lamprey population with or without changing gender functionality coexists.

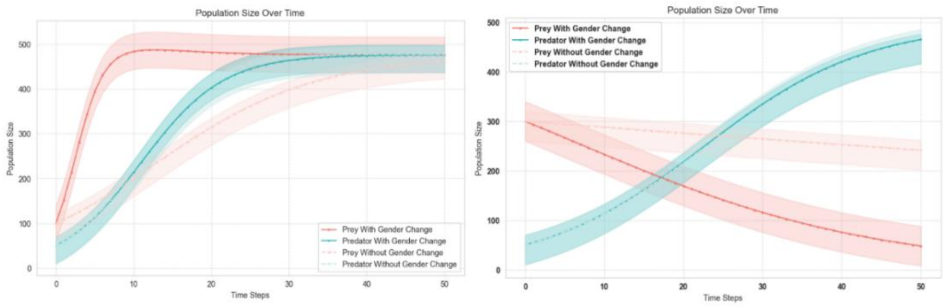


(a) Shannon-Wiener Index over time (b) Competition Index over time

Figure 3. S-W index and competition index over time

Figure 3(a) illustrates that over time, the Shannon-Wiener index of the ecosystem where lamprey populations with different sexual functions coexist fluctuates significantly, indicating that altering the characteristic of sex does not have a significant impact on species diversity. Concurrently, as shown in Figure 3(b), the competition index increases over time, suggesting that the modification of sexual function contributes to gaining an advantage in interspecific competition.

To further investigate the impact of variable sex traits of lamprey on ecosystem stability, this article considered predator-prey relationships in the ecosystem, with lamprey acting as predators and being simultaneously preyed upon by other species. To reflect the ecosystem, this article use the Lotka-Volterra model to simulate the dynamics of these three layers of the food chain.



(a) Lampreys and the Upper Trophic Levels (b) Lampreys and the Lower Trophic Levels

Figure 4. Coefficient of Variation Over Time

Figure 4(a) presents the population dynamics over time between lampreys with and without the sex-changing mechanism and their predators. It can be observed that lampreys capable of changing sex, as the prey, exhibit a faster increase in numbers during the growth phase compared to those that do not change sex. This is attributed to the flexibility and adaptability gained from changing sex in response to environmental changes, which gives them an advantage over the control group when being preyed upon. The predators show little difference under both conditions, indicating that the lampreys have a minimal impact on the predator populations within the ecosystem.

Figure 4(b) illustrates the population dynamics over time between lampreys with and without the sex-changing mechanism and their prey species. It is evident that the lampreys capable of changing sex, as predators, do not exhibit significant changes, whereas their prey species show a more rapid decline during the phase when the lampreys undergo sex change, compared to the control group, resulting in a higher predation rate. This suggests that lampreys have a more pronounced effect on the food species populations within the ecosystem.

3. The dynamic model of lampreys and parasites

3.1. The population dynamics model

3.1.1. The establishment of model.

This article were interested in how other parasite populations in the ecosystem are affected by lamprey sex changes. The approach to address this issue involves developing dynamic equations for both the lamprey population and the parasitic population, taking into account the impact of fluctuating environmental resources. For the dynamic equation of the female lamprey population, it is essential to consider not only the initial quantity, growth rate, and mortality rate of female lampreys but also the influence of different sex ratios on their fertility rate. Moreover, given the significant effect that the parasitic population has on female lampreys, this factor must also be incorporated into the population dynamic equation. The dynamic equation for the male lamprey population follows a similar pattern, but the coefficients may vary under different environmental conditions. Additionally, as the proportion of females to males differs across various environments, the model must reflect the environmental impact on the lamprey population as well.

In this model, setting different growth rates for females and males under different environmental conditions achieves this effect, taking into account the birth rates after gender transformation. Equation (11) demonstrates the dynamic equations for female and male lamprey populations:

$$\begin{cases} \dfrac{dN_f}{dt} = [r_f \cdot (1+\gamma_f \cdot sr)] N_f \left(1 - \dfrac{N_f + \alpha_1 \cdot P}{K_1}\right) - m_f N_f - \beta_f N_f P \\ \dfrac{dN_m}{dt} = [r_m \cdot (1+\gamma_m \cdot (1-sr))] N_m \left(1 - \dfrac{N_m + \alpha_1 \cdot P}{K_1}\right) - m_m N_m - \beta_m N_m P \end{cases} \tag{11}$$

In these equations, N_f, N_m represent the population quantities of male and female lampreys, respectively; r_f, r_m represent the population growth rates of male and female lampreys, respectively; m_f, m_m represent the death rates of male and female lampreys, respectively; γ_f, γ_m represent the impact of reproductive behavior on the lifecycles of male and female lampreys, respectively; α_1 represents the factor of predation on parasites for male and female lampreys; β_f, β_m represent the competition relationship factors between male and female lampreys and parasites; K_1 represents the maximum carrying capacity of lampreys in the ecosystem; P represents the total quantity of other parasites.

For the dynamic equation of the parasitic population, the overall approach is similar to that of the lamprey population dynamic equation. Parasites are influenced by lampreys in terms of predation, competition, and other relationships. Additionally, the model considers the saturation effect of parasite capacity within the ecosystem environment. Thus, this article obtain the equation model as represented by Equation (12):

$$\frac{dP}{dt} = r_p \cdot P \cdot \left[\frac{(P + \beta_f \cdot N_f + \beta_m \cdot N_m)}{K_2} - 1\right] + \alpha_2 \cdot (P \cdot N_f + P \cdot N_m) - m_p \cdot P \tag{12}$$

Where, r_p, m_p represent the growth rate and death rate of parasites, respectively; α_2 represents the impact of parasites parasitizing lampreys.

For the equation representing changes in environmental resources, both consumption and regeneration of the environment are considered. Since parasites have much smaller volumes compared to lampreys, the consumption of environmental resources by parasites is negligible in this model. Therefore, the equation for changes in environmental resources can be represented as shown in Equation (13):

$$\frac{dE}{dt} = \varepsilon \cdot (E_{\max} - E)\left(1 - \frac{E}{E_{\max}}\right) - \left(1 - \frac{E}{E_{\max}}\right)(E - E_{\min})\frac{E}{E_{\max}}(N_f + N_m) \tag{13}$$

3.1.2. Model solving.

Combining the above equations, they will be written into MATLAB. At the same time, initial conditions will be set, such as environmental conditions, initial quantities, various rates of change, etc., for solving and visual analysis. The solution strategy for this problem is to set different states of parasites and observe the changes in various populations under the presence or absence of lamprey gender transformation mechanisms. In this model, parasites are divided into two categories: one primarily parasitizing lampreys and the other competing with lampreys. For each scenario, population change curves are plotted to clearly illustrate how each population changes over time and to analyze the relationships between the curves.

3.2. Results and analysis

For the category of parasites primarily competing with lampreys, Figures 5(a) and (b) show the population change curves under the presence and absence of lamprey gender transformation mechanisms, respectively. Figure 5(a) depicts a scenario with unfavorable environmental conditions, where female juvenile lampreys transform into male lampreys.

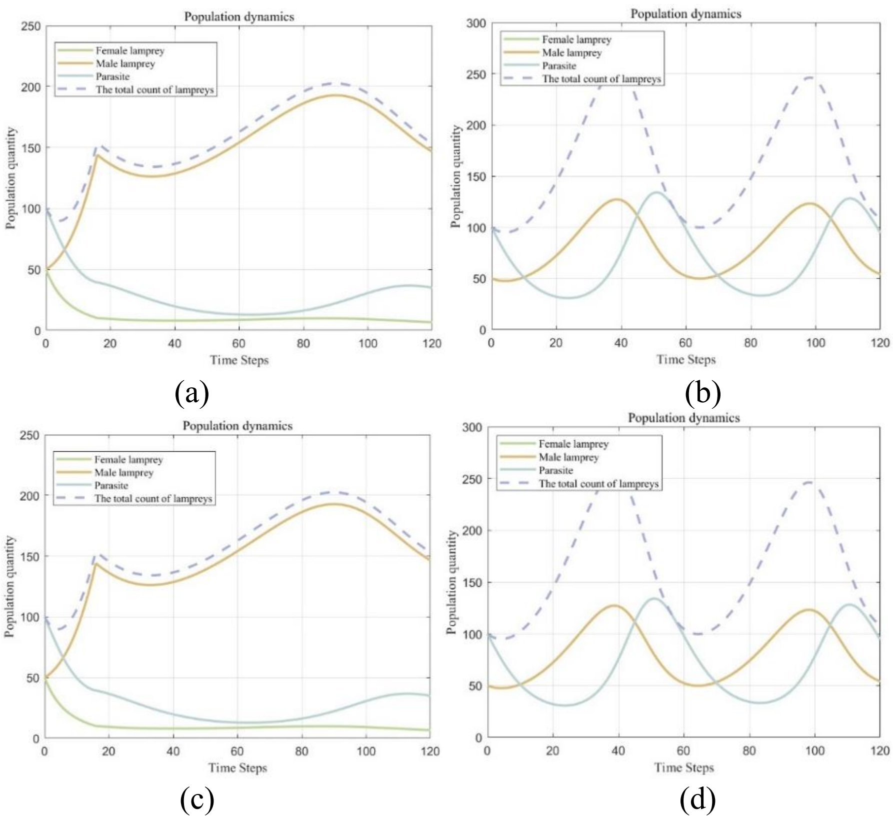


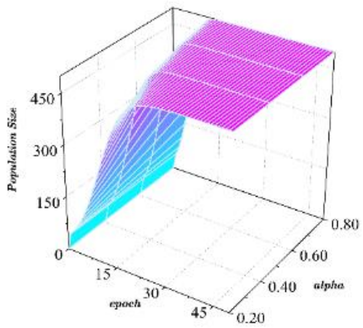
Figure 5. Competitive comparison and parasitic comparison

This article conclude that parasites competing with lampreys are constrained by the development of lampreys for a certain period. Under unfavorable environmental conditions, as females gradually transform into males, this type of parasite is gradually suppressed due to the strong competitive ability of males. However, after a period of time, the scarcity of female lampreys limits the unrestricted growth of male lampreys in terms of birth rates, leading to a downward trend in the number of male lampreys. This results in a slight increase in the number of these parasites, demonstrating a normal scenario of predation and competition. In contrast, in the absence of a sex change mechanism, lampreys and parasites are in a normal state of predation and competition in the same natural environment, with the growth of parasites lagging behind that of lampreys for a certain period.

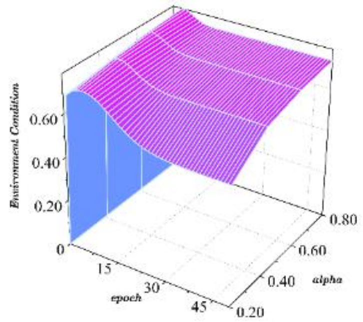
For the parasites that primarily parasitize lampreys, Figures 5(c) and (d) depict the population change curves under the presence and absence of lamprey sex change mechanisms, respectively, with environmental settings consistent with the above description. This article can observe that initially, when there is a large number of lampreys, parasites reproduce abundantly, but the maximum values reached in the two scenarios are slightly different. Furthermore, after reaching the maximum values, the conditions for the survival of parasites on male lampreys become less favorable due to their stronger survival abilities after females have transformed into males, resulting in a smaller maximum value for the parasite population. Additionally, the parasite population almost approaches zero afterward, which is also a result of the gradual improvement in environmental conditions. In contrast, without a transformation mechanism, the parasite population fluctuates with the increase and decrease of lampreys, consistent with parasitic conditions.

In summary, lampreys with gender transformation mechanisms do not have an advantage over these two types of parasites. They may somewhat inhibit the growth of parasites.

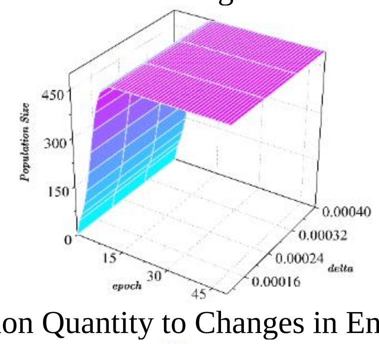
4. Sensitivity analysis



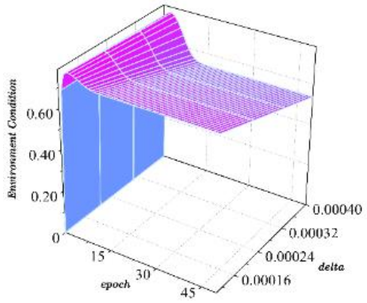
(a) Population Quantity to Changes in Env Growth Rate



(b) Env Conditions to Changes in Env Growth Rate



(c) Population Quantity to Changes in Env Cons Rate



(d) Env Conditions to Changes in Env Cons Rate

Figure 6. Sensitive Analysis

The figures 6(a)-(d) displayed depict sensitivity analyses for the gender determination model in response to changes in environmental growth rate and environmental consumption rate. It is evident that the model is more sensitive to changes in environmental growth rate compared to environmental consumption rate. This sensitivity is attributed to the considerably larger magnitude of environmental growth rate in this model, aligning with normal modeling patterns. Additionally, as environmental growth rate increases, environmental conditions improve, while an increase in environmental consumption leads to deteriorating environmental conditions, further validating the model's rationality.

5. Conclusion

This study's findings underscore the intricate dynamics of sex ratio adjustment in lampreys as a strategic response to resource availability, offering valuable insights into the biological mechanisms that underpin species survival and adaptation. The sex determination model this article developed not only provides a comprehensive evaluation of lampreys' ecological performance but also highlights the significance of such abilities in the context of environmental challenges and biodiversity conservation.

The practical implications of our research are manifold. Firstly, it contributes to the broader understanding of how species can adapt to changing environments, which is increasingly relevant in the face of global climate change. Secondly, our model can serve as a tool for conservation biologists to predict and manage the impacts of human activities on lamprey populations and their ecosystems. By revealing the conditions under which sex-changing abilities do not confer a competitive advantage against parasites, our study also emphasizes the complexity of ecological interactions and the potential limits of certain adaptive strategies.

In conclusion, our work take into account the intricate balance of ecological factors that influence species' survival, it also underscores the importance of continued research into the adaptive capabilities of species, as such knowledge will do help for the development of effective conservation strategies in a rapidly changing world. Moreover, our model can be applied to ecological restoration projects to enhance the resilience of specific species populations by simulating and optimizing sex ratios. For further study, the research can be expanded to the impact of sex ratio adjustments on ecosystem services and functions, as well as the long-term sustainability of these adaptive strategies in the face of global changes.

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