A study on the ecological environment influenced by the sex ratio of lampreys based on logistic and dynamic analysis model

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Abstract. Lamprey sex determination is influenced by factors such as larval growth rate and food availability. When food is plentiful, males make up approximately half of the population. However, in conditions of food scarcity, the proportion of males can increase dramatically, reaching up to 78%. This study investigates how changes in lamprey sex ratios can affect the abundance and distribution of the species, and ultimately, the stability of the ecosystem. This study developed a logistic growth model to simulate the ecosystem of the Great Lakes, using differential equations to analyze the temporal changes in lamprey populations over time. In addition, this study established a dynamic analysis model to predict future population trends based on varying environmental conditions. This study results show that an increased proportion of males leads to exponential growth in the lamprey population, which in turn significantly depletes the available food supply and reduces predator numbers. This imbalance causes large fluctuations in habitat occupancy, reproductive rates, and the overall health of the ecosystem. This research underscores the importance of understanding how sex ratio variability can influence ecosystem dynamics and species distribution, providing valuable insights into maintaining ecological balance in changing environments.

Keywords: Lamprey Sex Ratios, Logistic Growth Mode, Dynamic Analysis Model, Ecosystem Stability, Species Abundance and Distribution.

1. Introduction

The complexity and dynamism of ecological environments necessitate that key species adapt in a timely manner. Lampreys serve as a compelling example of this [1], particularly in their ability to adjust sex ratios in response to environmental factors [2]. In some studies, the sex ratio is closely related to population development, indicating the importance of sex ratio [3]. Lamprey sex determination is influenced by larval growth rates and food availability [4-5]. When food is plentiful, the proportion of males in the population decreases. Conversely, during periods of food scarcity, the proportion of males can rise to 78%. This significant variation underscores the need for models that explore how changes in sex ratios impact species populations and ecological balance.

Recent studies have extensively explored lamprey dynamics through modeling. Huang Meng (2021) developed the OSMOSE-ECS model to simulate the East China Sea ecosystem, focusing on 19 major economic species, including lampreys. This model, under no-fishing conditions, revealed that while average biomass remained stable, trophic levels declined, and fish size decreased over a 10-year period. Additionally, Li Yuesong (2021) reviewed lamprey biology and constructed an ecological model to examine the impacts of climate change and marine variability on resource replenishment. His findings highlighted significant effects of environmental changes on lamprey populations and resource dynamics.

Despite the valuable insights provided by existing models, they often fail to fully capture the comprehensive impacts of long-term sex ratio changes on populations and ecosystems. The limitations of these models include a lack of dynamic analysis of sex ratio variations under different environmental conditions. Our study addresses these shortcomings by developing a refined logistic growth model and dynamic analysis model. These models offer a more accurate simulation of sex ratio changes and their effects on lamprey population abundance and ecosystem stability, providing a scientific basis for maintaining ecological balance.

2. The basic fundamental of Logistics growth model and Dynamic analysis model

2.1. The structure of Logistics growth model

The simple exponential growth model can provide an adequate approximation to such growth for the initial period [6-7]. But the model does not accommodate growth reductions due to intraspecific competition for environmental resources such as food and habitat. Therefore, a logistics growth model is established, and the carrying capacity K is introduced to form the numerical upper limit of the growth scale. Figure 1. Logistics growth model structure.

The general model of Logistics growth model consists of three basic elements [8-10], which are:

(1) The input layer of the logistic regression model consists of a series of features that describe the basic information of the samples. In our study, input features might include the sex ratio of lampreys, environmental variables (such as water temperature and habitat quality), and biological parameters (such as birth rates and mortality rates). These features can be represented by the following input vector: $X = [x_1, x_2,..., x_n]$ where x_i represents the value of the $i-th$ feature, such as sex ratio or environmental factors.

(2) Although the logistic regression model does not have an actual hidden layer, its core computation involves an "implicit" linear combination process. In logistic regression, input features are combined through weighted summation and a bias term to form a linear expression: $z = w^T x + b$ where w is the weight vector, x is the input feature vector, and b is the bias term. The result z of this linear combination is a key factor influencing the classification outcome, reflecting the combined effect of the input features.

(3) The output layer applies an activation function (the sigmoid function) to transform the result of the linear combination into a probability value. The formula for the sigmoid function is: $\sigma(z) = \frac{1}{1+e^{-z}}$ This probability value represents the likelihood that the lamprey population belongs to a specific category (e.g., whether changes in the sex ratio significantly impact population abundance). Based on this probability, we can perform binary classification to determine whether changes in the sex ratio have a significant impact on population stability.

We can get a new formula as follows,

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) \tag{1}$$

Where r is the intrinsic growth rate and represents growth rate per capita, K is the maximum number of individuals the population can sustain in the environment, $\left(1 - \frac{P}{K}\right)$ is the fractional deficiency of the current size from the saturation level. The logistic analysis schematic is shown in Figure 1.

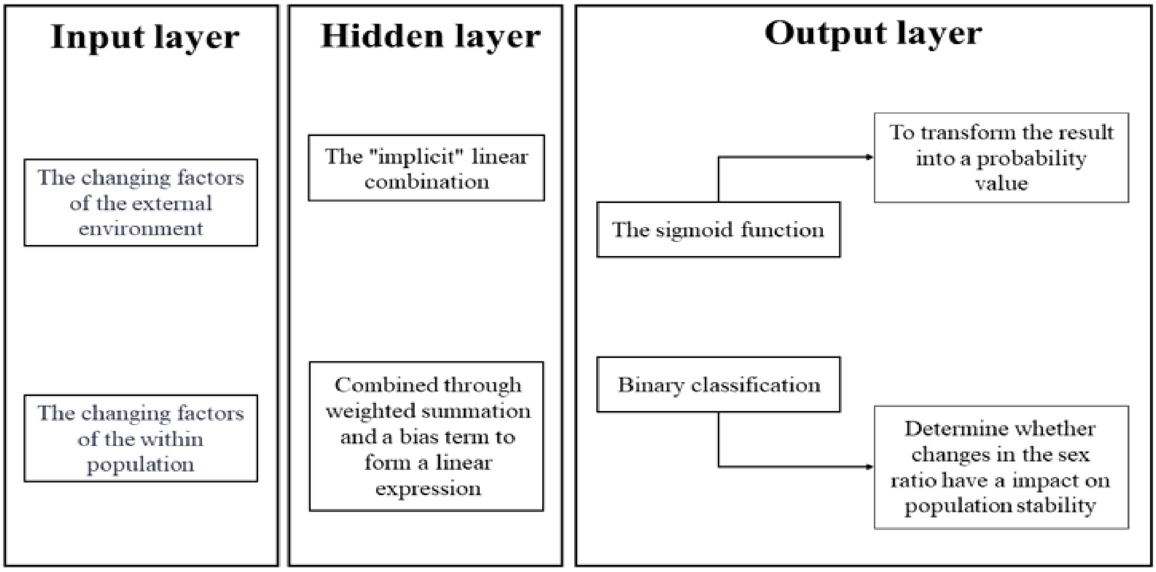


Figure 1. Logistics growth model structure.

2.2. The determination of Dynamic analysis model [11]

The dynamic analysis model, a sophisticated extension of traditional population growth models, is designed to predict the population growth rate of the lamprey eel with greater precision and adaptability. Unlike the simple exponential growth model, which offers a rudimentary approximation of population expansion during the initial phase, it fails to account for the inevitable slowdown in growth due to intraspecific competition for limited environmental resources such as food and habitat. To address this shortfall, the dynamic analysis model incorporates a more nuanced approach by introducing the concept of carrying capacity, denoted as K, which represents the upper boundary of sustainable population growth. This model dynamically adjusts to reflect changes in the environment and the population's interactions, providing a more realistic and responsive framework for forecasting the growth trajectory of the lamprey eel population. By considering factors such as resource availability, predation, and environmental fluctuations, the dynamic analysis model offers a robust tool for ecological research and conservation efforts.

The dynamic analysis model consists of five basic elements, which are:

(1) Integration of Environmental and Biological Parameters: The dynamic analysis model begins by integrating a variety of parameters that influence population growth. These include not only biological factors like birth and death rates but also environmental factors such as resource availability and habitat quality.

(2) System of Differential Equations: At its core, the model employs a system of differential equations that describe the rates of change in population size over time. These equations take into account the interactions between different age classes, sexes, and the carrying capacity of the environment.

(3) Nonlinear Activation Functions: To mimic the real-world complexity of population dynamics, the model incorporates nonlinear activation functions. These functions ensure that the model's output is not only a linear response to input changes but also reflects the thresholds and saturation points that are characteristic of biological systems.

(4) Feedback Mechanisms: The model includes both positive and negative feedback mechanisms to represent the self-regulating nature of ecosystems. For instance, as the population approaches the carrying capacity, competition for resources intensifies, leading to a decrease in the growth rate—a negative feedback loop.

(5) Iterative Process and Calibration: The dynamic analysis model is not static; it is calibrated and validated against empirical data through an iterative process. This involves adjusting model parameters to ensure that the model's predictions closely match observed population trends.

$$\frac{dF}{dt}=r_F-d_FF+b_FaPF \tag{2}$$

$$\frac{dP}{dt}=r_P-aP(M+F) \tag{3}$$

Where P is prey population, t is time F is population size of female lampreys, a is probability of prey being eaten, is reproduction rate of female lampreys, is predatory efficiency of female lampreys, is mortality rate of female lampreys, is natural growth rate of prey, M is population size of male lampreys.

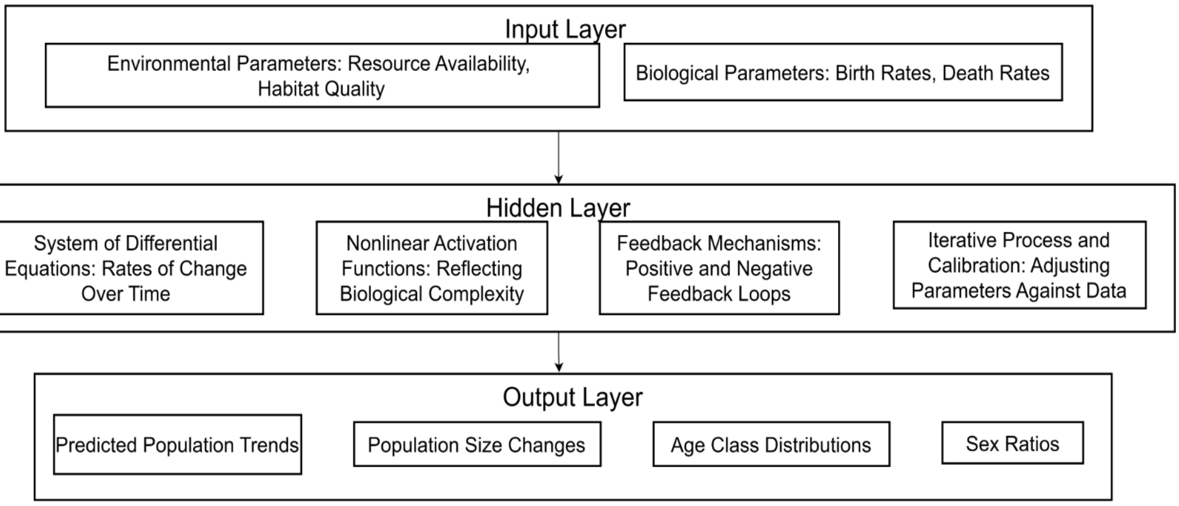


Figure 2. Dynamic analysis model structure.

As is shown in Figure 2, a dynamic analysis model operates on the principle of simulating how a system's variables interact and evolve over time, providing insights into its behavior under different conditions. This model offer an overview by integrating various factors and parameters to predict outcomes and assess the impact of changes within the system. However, applying dynamic analysis models can be challenging due to the complexity of accurately representing real-world systems.

3. Results

3.1. The results of Logistics growth model [12-13]

In this section, we established a Logistics growth model to find out the impact of different sex ratios of lampreys on their population changes. Next we analyze the results.

The population model graph and the chart showing the changes in the male ratio over time for the sea lamprey population are presented below, as shown in Figure 3 and Figure 4.

Observing the Logistic growth model equation and the population growth model graph, we can discern the trend of sea lamprey population size, $P(t)$ changing with time, t. As $P(t)$ approaches K, the growth rate begins to decrease, and the term $e^{\wedge}-rt$ in equation (1) gradually approaches 0, causing the denominator to approach 1, leading $P(t)$ to approach K. This indicates that sea lamprey population growth slows down as it approaches the carrying capacity of the environment, eventually reaching stability. At this point, we refer to it as the sea lamprey reaching the population equilibrium point.

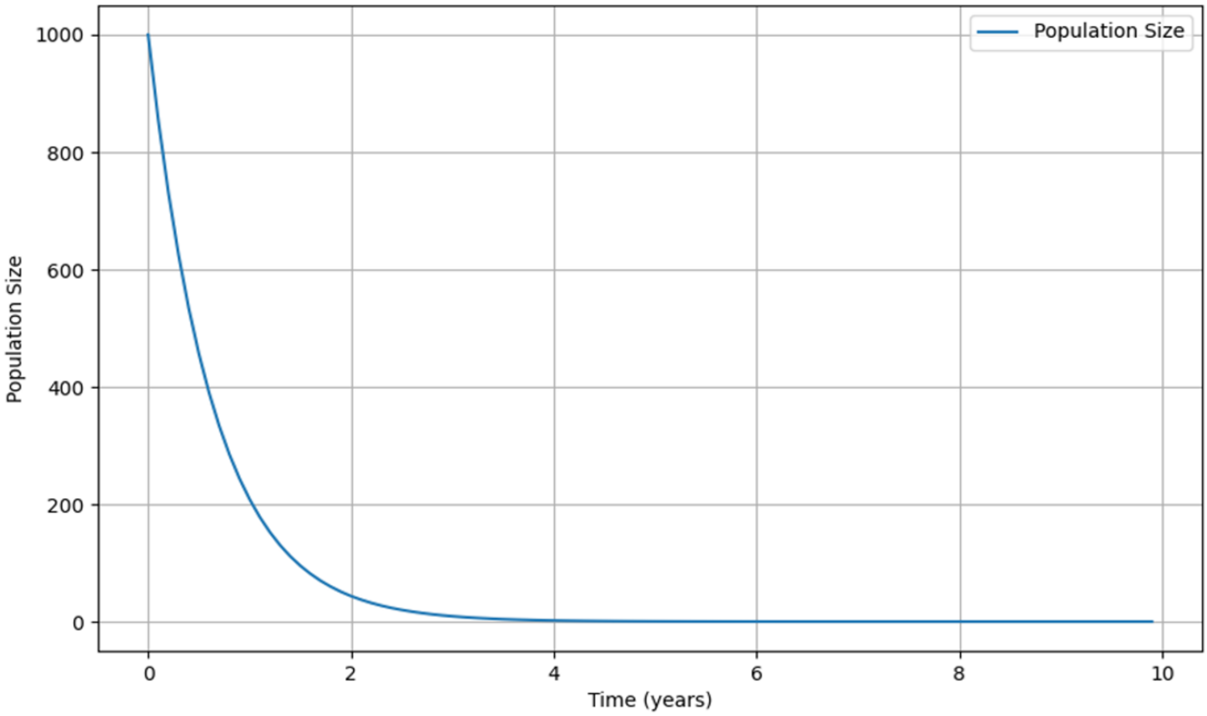


Figure 3. Custom Population Model.

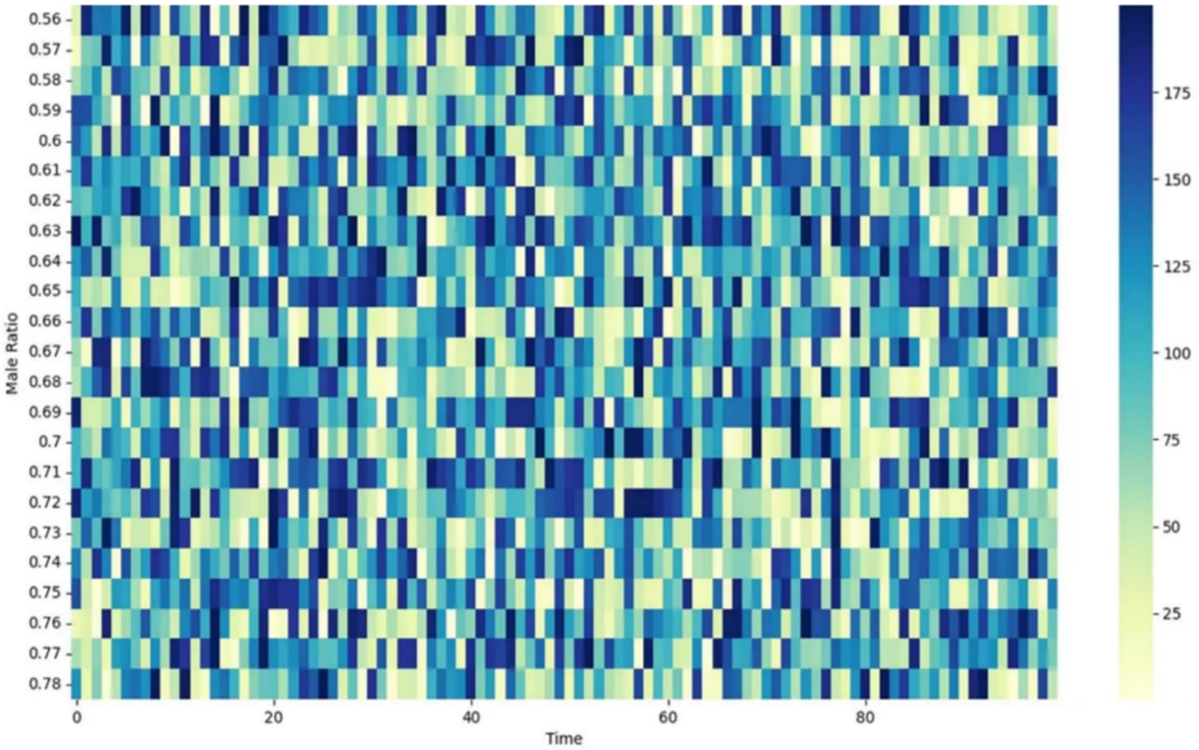
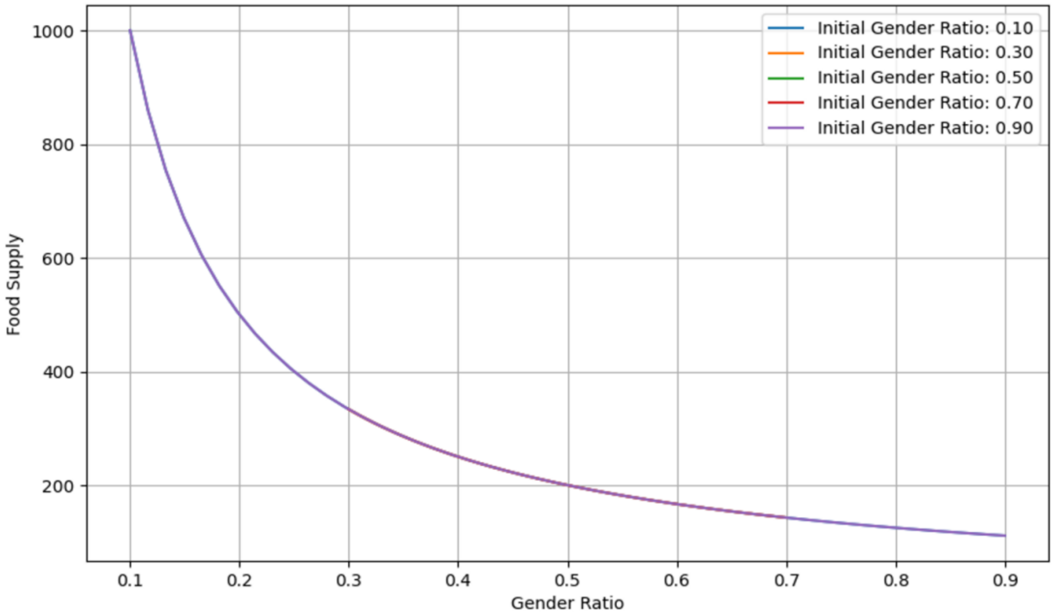


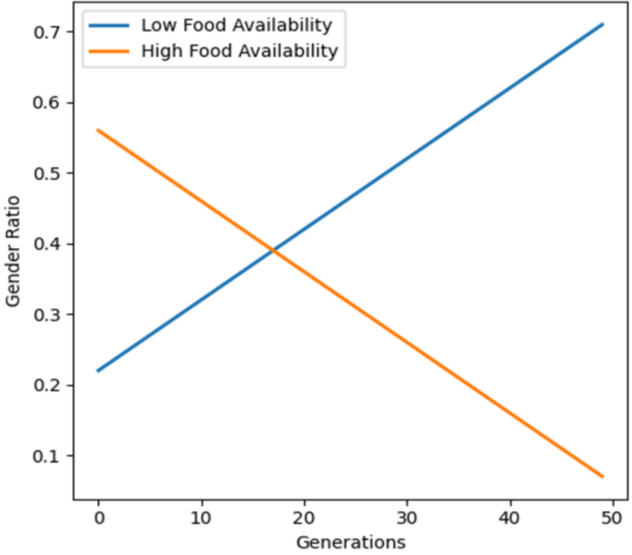
Figure 4. Lamprey Population Size across Time and Male Ratios.

3.2. The results of the dynamic analysis model

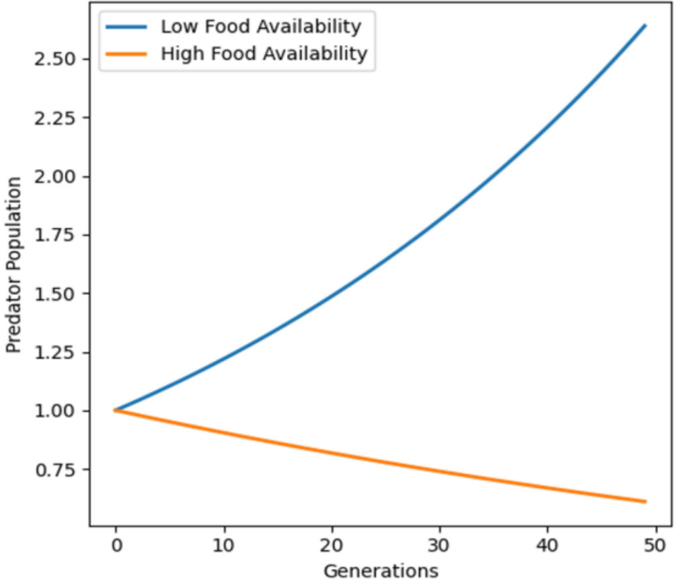
We constructed a dynamic analysis model to delve into habitat occupancy rates, food supply relationships, and the effects of predator populations on lamprey's populations. The sex ratio plays an important role in the population of lampreys. Considering the role of lampreys as invaders in the Great Lakes ecosystem, it is speculated that the sex ratio of lampreys has a large negative effect on the ecosystem where lampreys live. The model is as shown in Figure 5 (a-e).



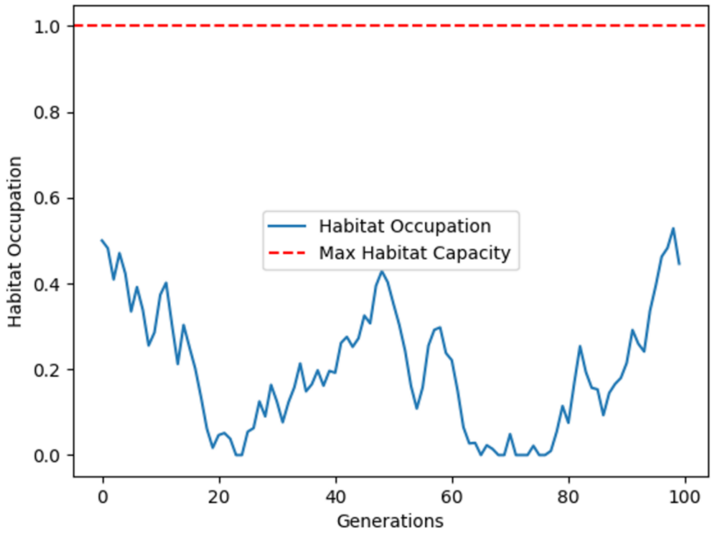
(a) Effect of Gender Ratio on Food Supply



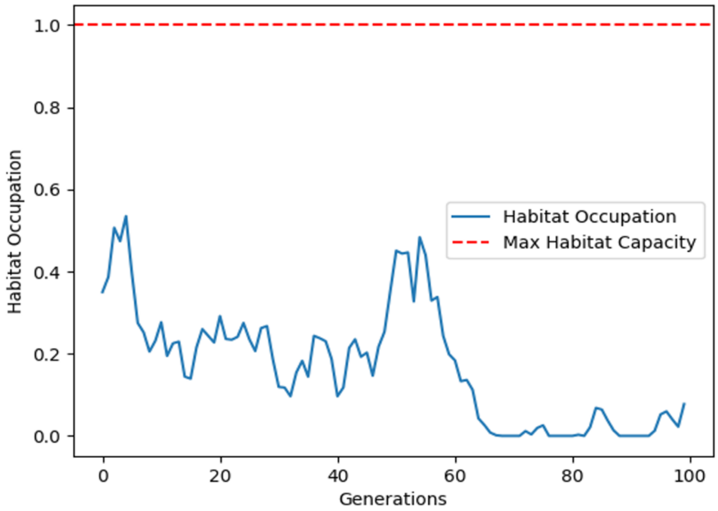
(b) Effect of Sex Ratio on Food Availability;



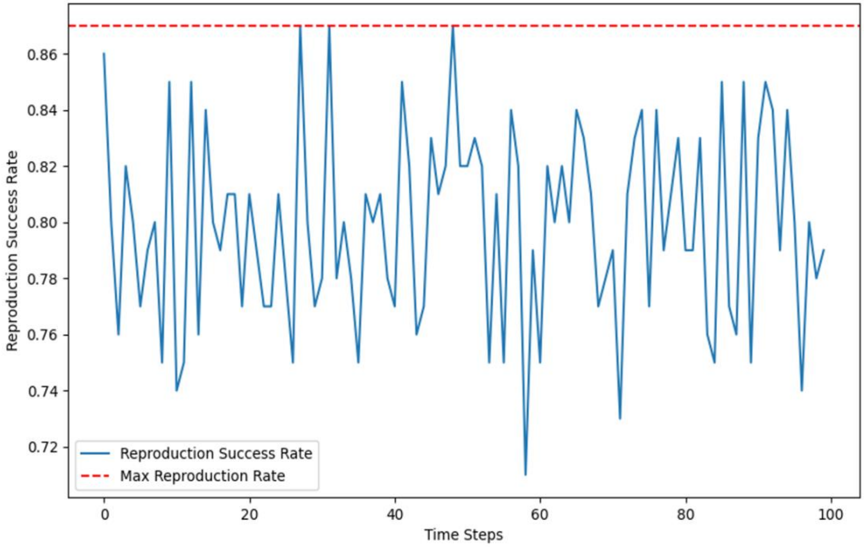
(c) The Impact of Food Supply on Predator Populations



(d) Habitat Occupancy over Time



(e) Changes in Resource Habitat Occupancy



(f) Effect of Sex Ratio on Reproduction Rate

Figure 5. The construction of the dynamic analysis model.

Figure 5 (a) illustrates the effects of different initial sex ratios (0.10, 0.30, 0.50, 0.70, 0.90) on food supply. As the sex ratio increases, food availability decreases significantly, possibly due to increased food consumption by males, resulting in less available food. Too high a male ratio can quickly exhaust food resources and affect the stability of the ecosystem. Conversely, a higher proportion of women means that food is consumed at a slower rate, helping to maintain a stable food supply. In Figure 5 (b-c), the lack of food supply has led to a decline in predator numbers over several generations due to insufficient food. Figure 5 (d) shows an initial rapid decline in habitat occupancy followed by a slow recovery with fluctuations, reflecting ecological and environmental factors. Fluctuations in habitat occupancy was shown in Figure 5 (e), which may be due to environmental instability or complexity of population dynamics. Figure 5 (f) shows significant fluctuations in reproductive rate, possibly influenced by changes in sex ratio and habitat occupancy. Overall, these findings suggest that sea lampreys population dynamics are influenced by a variety of ecological factors, including food availability.

4. Conclusions and Outlooks

In this study, we investigated the impact of sex ratio changes in lampreys on species abundance and ecological balance by integrating logistic regression and dynamic analysis models. We addressed the problem of how variations in sex ratios affect population stability and ecosystem dynamics. To achieve this, we developed a logistic regression model to classify and predict the influence of sex ratio variations on population abundance. Additionally, a dynamic analysis model was employed to simulate population growth and the ecological feedback mechanisms under varying conditions. Our results indicate that changes in sex ratio have significant effects on population stability and can lead to shifts in ecological balance. The models we established provide valuable insights into the dynamics of lamprey populations and can be applied to other species facing similar ecological challenges. Furthermore, these models offer a framework that can be used for managing and conserving species populations, ensuring their sustainability in changing environments.

Despite the robustness of our models, several limitations remain. The logistic regression model assumes a linear relationship between inputs and outputs, which may oversimplify complex biological interactions. The dynamic analysis model, while comprehensive, relies on parameter estimates that could benefit from more precise calibration. Future improvements could involve incorporating more nuanced data and exploring non-linear models to better capture ecological complexities. Additionally, expanding the models to include a broader range of species and environmental factors could enhance their applicability and accuracy in various ecological contexts.

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