

Research on the Dynamics of Sea Lamprey Sex Ratio and Its Ecological Impacts in the Lake Ontario Ecosystem Based on the OLED Model

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Abstract: This study focuses on the sea lampreys that have invaded the Great Lakes. Considering the significant impact of their sex ratio changes with the environment on the ecosystem, the aim is to construct a model to explore its mechanism. Data from various sources such as government departments, scientific research institutions, and academic articles were collected and preprocessed. The Lake Ontario Lamprey Ecosystem Dynamics Model (OLED) was created, which consists of the Sex Ratio Relationship (SRR), Lamprey Life Cycle (LLC), and Lake Ontario Species Survival (LOSS) modules. The Lasso regression and other algorithms were used to analyze the impact of environmental factors on the sex ratio. Based on the Lotka-Volterra and other models, the relationships between sea lampreys and other species were studied. The Gray Forecast Model was also adopted to predict relevant variables and calculate the sex ratio. The results show that the changes in the sex ratio of sea lampreys significantly affect the ecosystem, such as influencing fish populations and nutrient cycling. Moreover, the model is robust under small data perturbations and is sensitive to the reproduction rate. This research provides theoretical support for the ecological control of sea lampreys.

Keywords: Sea lamprey, Sex ratio, OLED model, Ecosystem

1. Introduction

1.1. Research Background

Sea lampreys are a notable invader in the Great Lakes, impacting native fish populations severely since their introduction in the 20th century [1]. This significant impact arises from their ability to adapt their sex ratio to environmental conditions, an unusual trait that allows them to optimize reproduction and survival in fluctuating environments. Specifically, the sex of sea lampreys is determined by their growth rates during the larval stage, which are directly influenced by the availability of food resources. Male sea lampreys comprise up to 78% of the population in environments where food availability is low. This adaptation plays a critical role in the survival strategies of the species.

This phenomenon affects the population of sea lampreys and has broader implications for the ecosystem's health and stability. Consequently, understanding and addressing the intricate role of the sex ratio variation is paramount. To this end, developing mathematical models to simulate these dynamics is essential for effectively managing sea lamprey populations and protecting the ecosystems of the Great Lakes.

1.2. Literature review

Agriculture plays a crucial role in the global economy and social stability. The stability and growth of crop yield are essential for meeting the demands of the ever-increasing population. With the development of technology, machine learning techniques are increasingly applied in the agricultural field, providing new methods and means for crop yield prediction. Accurate prediction of crop yield helps farmers to arrange planting plans reasonably and optimize resource allocation, and also provides a scientific basis for the government to formulate agricultural policies. This study uses relevant datasets and explores the impact of climatic factors and agricultural inputs on crop yield through multiple machine learning models to construct effective prediction models and provide support for agricultural production.

Numerous studies have been conducted on the stability of ecosystems, focusing on the ecosystems of the Great Lakes. W. Paul Sullivan et al. [2] have highlighted the significant impact of unchecked sea lamprey predation coupled with extensive fishing pressures. Notably, the fluctuating sex ratio of sea lampreys, driven by environmental changes, emerges as a crucial aspect of their survival. This paper primarily investigates the correlation between environmental shifts and changes in the sex ratio of sea lampreys. Megan A. Shavalier et al. [3] have identified sea lampreys as hosts to diverse pathogens, with most also present in other fish species. Since infectious diseases compromise fish health, growth, and reproduction, this paper delves deeper into examining the dynamics between sea lampreys and their associated pathogens.

Based on this analysis, we employ regression algorithms, differential equations, various coefficients, and proposed methodologies to unravel the complexities behind the sex ratio shifts in sea lampreys. Traditional regression analysis utilizes the least squares method introduced by Adrien-Marie Legendre [4] for linear regression, supplemented by correlation coefficients for evaluation. This approach, however, may not account for potential linear relationships among independent variables, where one may serve as a linear combination of others. To address multicollinearity, ridge regression introduces a regularization penalty factor to refine the estimation process. Robert Tibshirani [5] introduced the Least Absolute Shrinkage and Selection Operator (Lasso), a method of compression estimation that incorporates an L1 regularization penalty to streamline variable coefficients, effectively nullifying those deemed insignificant or irrelevant, thereby facilitating feature selection.

Furthermore, to accurately model interspecies relationships, this study incorporates the Lotka-Volterra model [6], better for simulating interactions between lampreys and salmon. This model forecasts species fluctuations within ecosystems and accounts for interspecies impacts. Additionally, we adopt the Susceptible-Infective Model proposed by W. O. Kermack et al. to explore bacterial infection dynamics, enabling a detailed examination of sea lamprey infection patterns.

1.3. Our Work

This paper begins by collecting pertinent data and preprocessing it, including outlier removal and normalization. Subsequently, we introduce the Lake Ontario Lamprey Ecosystem Dynamics Model (OLED), consisting of three distinct modules: Sex Ratio Relationship (SRR), Lamprey Life Cycle (LLC), and Lake Ontario Species Survival (LOSS). Initially, the SRR module investigates the

correlation between environmental variables and the sex ratios of lampreys. The LLC module then determines lamprey’s birth and mortality rates, enabling the LOSS module to assess the population dynamics of lampreys and their interactions with other species. In addition, we also combine the Gray Forecast Model to predict the number of salmon in the coming years and thus predict the sex ratio of lampreys. A sensitivity analysis is performed to evaluate the model’s robustness, and validation procedures are undertaken to ensure its accuracy. Figure 1 is a flowchart of our whole work framework:

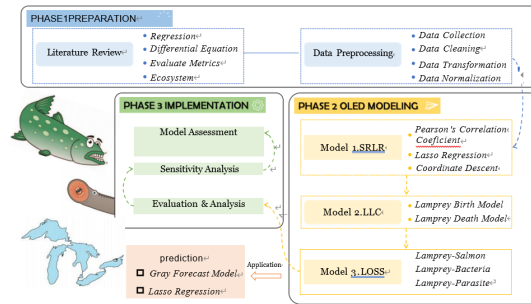


Figure 1: Framework of our work

2. Data Introduction

We have collected data from various sources to ensure a comprehensive foundation for our model. These include government departments [7], scientific research organizations [8], and scholarly articles [9], the aggregation of this data, detailed in Table 1.

Table 1: Key data and their sources

Data	Sources
Lamprey Sex Ratio	Hansen, MJet al. [9]
Predator Fish Numbers	Great Lakes Fishery Commission [10]
Prey Fish Numbers	Great Lakes Fishery Commission [10]
Water Levels	Great Lakes Integrated Sciences Assessments [8]
Water Temperature	U.S. Environmental Protection Agency [7]
Phosphorus Concentrations	State of the Basin Report[11]
Bacteria Infection Rate	Megan A. et al. [3]

In the data preparation phase, we transform the unstructured data into a structured dataset saved in CSV format for efficient processing with Python. This dataset covers annual data on lampreys and related ecological indicators from 2000 to 2015. We selectively normalize the data to enhance comparability among various indicators and reduce the influence of dimensional variations during analysis.

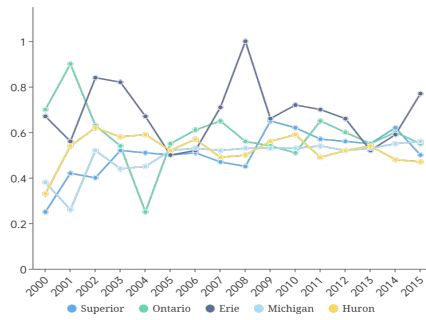


Figure 2: Variation in lamprey sex ratios in the Great Lakes from 2000 to 2015

Figure 2 illustrates the variation in the sex ratios of lampreys in the Great Lakes from 2000 to 2015, providing foundational data for our research. Given our research focus on the ecological condition of Lake Ontario, we specifically extract data on the variation in the sex ratio of lampreys in this lake. We observe that, compared to the other Great Lakes, the sex ratio of lampreys in Lake Ontario shows more pronounced fluctuations over the 15 years, a phenomenon we believe is closely related to the ecological environment of Lake Ontario.

3. OLED: Lake Ontario Lamprey Ecosystem Dynamics Model

To investigate the effects of sex ratio variations in sea lampreys on their population dynamics and the broader ecosystem, we develop the Lake Ontario Lamprey Ecosystem Dynamics Model (OLED), which consists of three interconnected modules: the Sex Ratio Lasso Regression Module (SRLR), the Lamprey Life Cycle Module (LLC), and the Lake Ontario Species Survival Module (LOSS).

3.1. SRLR: Sex Ratio Lasso Regression Module

This dataset includes counts of Walleye, Brown Trout, Coho Salmon, and Lake Trout, as well as measurements of phosphorus concentrations, water temperature, and rainfall. Walleye and Brown Trout are predators of sea lampreys, affecting their growth and reproduction. Coho Salmon and Lake Trout host the adult sea lampreys, which attach to them to draw blood. The phosphorus concentrations affect the amount of algae and plankton in the water, thus influencing the growth of sea lamprey larvae. All of these environmental factors impact the sex ratio of sea lampreys. To investigate the impact of these factors on the sex ratio, we begin by normalizing the collected variables. Then, we calculate the male ratio and its Pearson correlation coefficients ρ_i with other variables, selecting those with a greater impact and Figure 3 visualizes the results.

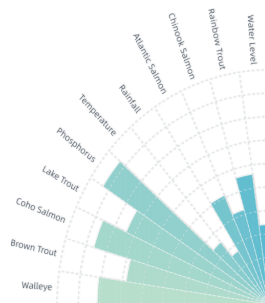


Figure 3: Correlation between sex ratio and various factors

We perform regression fitting by using the male ratio r as the dependent variable and the number of predators x_i ($i = 1, 2$), host numbers x_i ($i = 3, 4$), and concentrations of phosphorus x_5 as independent variables. To prevent multicollinearity and adjust the influence of different variables

on the sex ratio, we employ the Lasso Regression algorithm. The coefficients and their multiple correlation coefficient R are as follows:

Table 2: Coefficients of the lasso regression model

Coefficient	w0	w1	w2	w3	w4	w5
Value	0.195	-0.591	-0.571	0.463	0.437	0.783

The results are visualized in Figure 4, demonstrating the excellent fit of SRLR, with the distribution of the regression-derived sex ratios closely matching the observed data. This indicates a high level of accuracy in reflecting the actual sex ratio variations in sea lampreys, underlining the robustness in capturing the key relationships between environmental factors and the lamprey sex ratio.

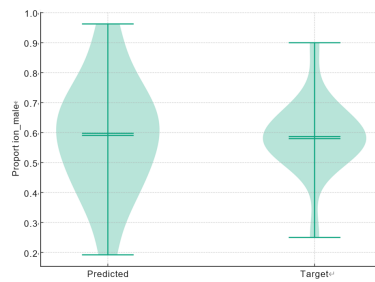


Figure 4: Violin plot of predicted and target proportion male ratio

3.2. LLC: Lamprey Life Cycle Module

In the lifecycle of sea lampreys, illustrated in Figure 5, birth and death represent the two pivotal phases. The sex ratio plays a vital role in influencing sea lamprey birth rates. Accordingly, we have developed a module to understand this dynamic based on several fundamental assumptions: The birthrate should be highest when the population’s sex ratio is balanced. As the sex ratio deviates from this equilibrium, the birthrate should decrease.

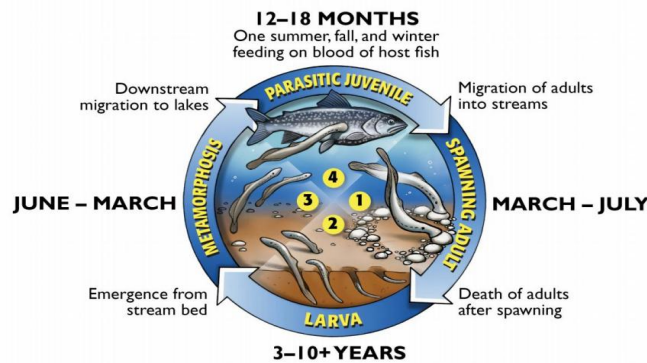


Figure 5: Life cycle of lampreys

3.3. LOSS: Lake Ontario Species Survival Module

The sea lamprey plays a significant role in the Lake Ontario ecosystem, as it is linked directly or indirectly to various species, including different fish, bacteria, and parasites. To study these relationships, we have developed three growth modules: the Lamprey- Salmon module, the Lamprey- Bacteria module, and the Lamprey-Parasite module. These modules are designed to explore the relationships between the sea lamprey and its hosts, bacterial infections, and parasites.

The Lamprey-Salmon module is based on the Lotka-Volterra model [6]. There have been disease outbreaks among wild and hatchery fish populations in the Great Lakes due to numerous endemic and emerging pathogens [12]. Similarly, bacterial infections have also been identified in sea lampreys of the Great Lakes, resulting insignificant disease outbreaks. Our research has shown a strong correlation between the rate of infection by *Aeromonas salmonicida* bacteria in sea lampreys and their sex ratio according to data we have collected [3].

3.4. Practical Application of OLED to Predict Sex Ratio

Based on our proposed OLED model, we can forecast future sex ratios of sea lampreys by predicting variables such as the number of predators x_i ($i = 1, 2$), host numbers x_i ($i = 3, 4$), and phosphorus levels in water x_5 . This capability of predicting lays a theoretical groundwork for the ecological control of sea lampreys. Given the short time series, limited statistical data, and incomplete information systems for these variables, we have employed the Gray Forecast Model [13].

Table 3: Predictive model parameters and error metrics

Indicator	Brown Trout	Coho Salmon	Lake Trout	Walleye	Phosphorus
a	-0.0024	0.0555	-0.0103	-0.0925	-0.0431
b	569483.5	232229.3	789474.7	3250.1	11.7
Error	0.5	0.6875	0.5	0.8125	0.75

We forecast the five variables using the GM(1,1) model, with parameters and errors as indicated in Table 3. Notably, this analysis directly utilizes the original data. Figures 6 and 7 showcase anticipated dynamics in species populations and the shifts in sex ratios.

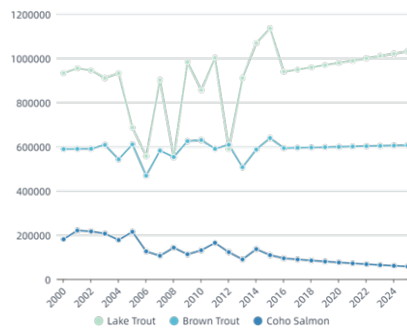


Figure 6: Lamprey Population from Historical Data to Future Forecasts (2000-2024)

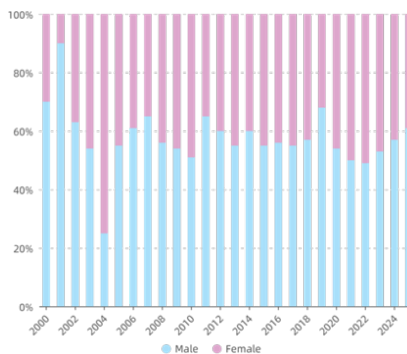


Figure 7: Lamprey Sex Ratios from Historical Data to Future Forecasts (2000-2024)

4. Results and Analysis

4.1. Impact of Lamprey Sex Ratio on Ecosystem Dynamics

The impact of sea lampreys altering their sex ratio significantly affects their habitat's ecological environment, particularly local fish communities and water nutrients.

According to the regression results above, it can be concluded that adjustments in the sex ratio of sea lampreys significantly impact their habitat's ecological environment, especially in terms of local fish communities and water nutrient components. Specifically, as the proportion of females in lampreys increases, so does their reproduction rate, leading to a larger population. This change causes lamprey larvae to consume more nutrients in Lake Ontario, depleting survival resources for local fish populations and negatively affecting their amounts. Moreover, since adult lampreys parasitize specific local fish, including Coho Salmon and Lake Trout, there is a notable negative correlation between the lamprey's female ratio and these fish populations. This discovery reveals that adjustments in the sex ratio of sea lampreys impact their population dynamics and have important implications for species diversity and nutrient cycling mechanisms across the entire ecosystem.

4.2. Sensitivity Analysis

In assessing the robustness of the Lake Ontario Lamprey Ecosystem Dynamics Model (OLED), we introduce random perturbations to the input data at levels of $\pm 3\%$, $\pm 5\%$, and $\pm 10\%$. The goal is to simulate real-world inaccuracies in data collection and evaluate the resilience to such disturbances. The Mean Squared Error (MSE) loss is calculated for each perturbation level to quantify the output deviation from the expected outcomes, shown in Table 4.

The OLED model exhibits commendable robustness to minor data perturbations ($\pm 3\%$ and $\pm 5\%$), maintaining a high degree of accuracy in its predictions. When the input data is subjected to these relatively small variations, the model's output remains relatively stable, with the predicted values closely aligning with the expected outcomes. This showcases the model's ability to handle minor fluctuations in the data, which are common in real-world ecological datasets due to measurement errors or natural variations.

However, when the data perturbation increases to $\pm 10\%$, the model's performance notably deteriorates. The Mean Squared Error (MSE) loss significantly increases, indicating a larger deviation between the predicted and actual values. This suggests that the model's internal structure and the relationships it has captured may not be as resilient to such substantial data changes. It could be due to the fact that the model's parameters and the algorithms used are optimized for a certain range of data variability. When this range is exceeded, the assumptions and approximations made during the model's construction may no longer hold.

Table 4: Sensitivity Analysis Results for Key Model Parameters (MSE)

Variation	Mortality Rate	Reproduction Rate	Human Intervention
$\pm 3\%$	0.012	0.015	0.010
$\pm 5\%$	0.020	0.025	0.017
$\pm 10\%$	0.035	0.045	0.030

5. Conclusions

5.1. Research Summary

This study constructed the OLED model to analyze sea lamprey sex ratio variation and its ecosystem role. The SRLR module identified key environmental factors influencing sex ratio using Lasso

regression. The LLC module explained the sex ratio-birth rate link, and the LOSS module explored species interactions. With the Gray Forecast Model, future sex ratios were predicted. The model showed robustness to small data perturbations ($\pm 3\%$ and $\pm 5\%$) but deteriorated at $\pm 10\%$. It provides support for ecological control, though improvements are needed.

5.2. Research Limitations

Despite the achievements of this study, several limitations exist. Firstly, the data used in the model mainly cover the period from 2000 to 2015. The relatively short time series may not fully capture the long-term and complex variations of the sea lamprey ecosystem. This could lead to uncertainties in the model's generalization ability for predicting future trends over longer time horizons. Secondly, although efforts have been made to collect data from multiple sources, there may still be some data gaps and inaccuracies. For example, the data on the specific interactions between sea lampreys and some rare or less-studied species in the Lake Ontario ecosystem might be insufficient. This could affect the comprehensiveness and precision of the LOSS module in depicting the entire ecosystem network. Additionally, the model assumes certain relationships between variables based on existing knowledge and data trends. However, in the real ecosystem, there could be more complex and nonlinear relationships that are not fully captured by the current model structure. This might limit the model's ability to accurately predict extreme or unexpected ecological events.

5.3. Future Directions

Future research could focus on several aspects. One important direction is to expand the dataset by collecting more long-term and detailed ecological data. This includes continuous monitoring of sea lamprey populations, their sex ratios, and relevant environmental factors over a longer period, preferably spanning several decades. Incorporating data from new monitoring technologies and more comprehensive sampling methods would enhance the data quality and quantity. Another area of research could be to further refine the model structure. Additionally, considering the impact of climate change on the Lake Ontario ecosystem and sea lampreys is crucial. Future studies could incorporate climate change factors such as temperature rise, precipitation variation, and extreme weather events into the model to analyze their combined effects on sea lamprey populations and the ecosystem. This would help in developing more adaptive and sustainable management plans for the Great Lakes ecosystem in the context of climate change.

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