Effects Of Lamprey Sex Ratio on Ecosystem Stability Based on Graph Neural Network and Deep Learning

Ru Li *

School of Information Science and Technology, Beijing University of Chemical Technology, Beijing, China, 100029

* Corresponding Author Email: 15110632798@163.com

Abstract. The purpose of this study was to explore the impact of the dynamic adjustment of the sex ratio of lamprey on the stability of the ecosystem. The ecological effects of the sex ratio under different resource conditions were analyzed by constructing logistic model, genetic algorithm and deep learning prediction model combined with graph neural network. The study found that the dynamic adjustment of gender ratio can significantly improve the robustness of the ecological network, and its stabilizing effect can be reflected through the network centrality and the optimization of community structure. The results of data visualization show that the coupling effect of gender ratio change and resource availability can be visualized through dynamic thermal map and three-dimensional interactive map. The innovation of this study is to introduce graph neural network and deep learning technology into ecological research, which effectively makes up for the shortcomings of traditional models in dealing with the dynamics of complex ecological networks, and provides a new analytical framework for the ecological mechanism of gender ratio regulation. In addition, the research and development of prediction tools based on deep learning has high application feasibility, which can provide accurate decision support for ecosystem management and help the sustainable management and protection of ecosystems.

Keywords: Gender ratio, Ecosystem stability, Graph neural network, Deep learning, Data visualization.

1. Introduction

Sex ratio is the core parameter of population dynamics, and its change can affect the stability of ecosystem through the cascade effect of food chain. Lampreys Anguilla is a typical environmental sex determining species, and its sex ratio shows a significant adaptive adjustment with the change of food resources. In the low resource environment, the proportion of males can reach 78%, while in the high resource environment, the proportion of males decreases to 56%. This phenomenon provides an ideal model for studying the interaction between gender ratio and ecosystem. Previous studies have shown that the imbalance of gender ratio may lead to the decline of population fertility, and then affect the stability of the ecosystem. For example, zhaolingling (2014) studied the impact of gender ratio imbalance on the success rate of population reproduction through statistical analysis [1], while fengyuting et al. (2024) analyzed the potential impact of gender ratio change on species diversity through field investigation [2]. These studies provide an important basis for understanding the impact of gender ratio change on ecosystem, but the quantitative analysis of the overall impact of gender ratio change on ecological network is still insufficient.

This study combines the classical Lotka Volterra model and modern graph neural network technology to build a comprehensive model to analyze the impact of gender ratio change on ecosystem stability. Lotka Volterra model can effectively describe the predator-prey relationship, but it is difficult to capture the nonlinear interaction in complex networks. In order to enhance the modeling ability of the model for the dynamic characteristics of complex ecological network, graph neural network and deep learning prediction model are introduced in this study. The introduction of graph neural network provides a new way for modeling the dynamic characteristics of ecological network. At the same time, deep learning technology shows a significant advantage in predicting environment driven gender ratio changes. The research purposes of this paper mainly include:

(1) Constructing an ecological network model with dynamic gender ratio.

(2) Reveal the mechanism of gender ratio adjustment on network stability.

(3) Develop prediction tools based on deep learning to provide decision support for ecological management.

2. Materials and methods

2.1. Data acquisition and preprocessing

The data of this study are from the open-source website, literature review, OECD and other related databases. It mainly collected the population dynamics data of lamprey sex ratio, and constructed a data set containing resource availability and sex ratio.

In the data preprocessing stage, the collected data is standardized first, and all eigenvalues are scaled to between 0 and 1 to eliminate the impact of different dimensions and orders of magnitude. Then, the outliers in the data were identified and processed by statistical analysis, and the key characteristics, such as resource volume, sex ratio and population density, were retained. In addition, noise reduction processing is carried out on the data to remove the noise points caused by measurement errors or data entry errors. These preprocessing steps provide high-quality data support for subsequent model training and validation.

2.2. Method introduction

Combined with genetic algorithm, graph neural network and deep learning prediction algorithm, the ecological effect of gender ratio change under different resource conditions was analyzed.

2.2.1 Genetic Algorithm

The Genetic Algorithm (GA) [3] was first proposed by Professor J.Holland of Michigan University in 1975. It is a global optimization algorithm that simulates biological evolution, using coding, selection, crossover, and mutation to iteratively search for optimal solutions. In this study, genetic algorithm is used to optimize the model parameters to improve the adaptability and prediction ability of the model.

2.2.2 Graph Neural Network

Graph Neural Network (GNN) [4] is a neural network designed for graph-structured data, capable of learning node features and topological information by aggregating neighbor characteristics to capture complex interactions. In this study, graph neural network is used to analyze the impact of gender ratio change on the topology of ecological network.

2.2.3 Deep learning prediction model

This study employs a DNN [5] as the prediction model, leveraging its ability to learn complex nonlinear relationships and automatically extract features from data to accurately predict gender ratio changes and their impacts on ecosystem stability. In this study, DNN is used to predict the dynamic changes of gender ratio under different resource conditions and provide decision support for ecosystem management.

3. Model establishment and solution

3.1. Model building

3.1.1 Gender ratio modeling

In order to study the impact of changes in sex ratio of lamprey on ecosystem stability, the logistic model [6] was used to describe the impact of food resource availability on the development rate of larval stage, thereby affecting the sex ratio. The logistic model is as follows:

$$R = \frac{1}{1 + e^{-r(T)(t-t_0)}} \tag{1}$$

where R is the probability of becoming a male (sex ratio), r is the growth rate, t_0 is the time when the sex ratio begins to change, and r (T) represents the effect of temperature T on the development rate.

The model can predict the changes of sex ratio of lampreys under different resource conditions, and provide the basis for the analysis of ecosystem stability.

3.1.2 Population dynamics modeling

Based on the classical Lotka Volterra equation, the population dynamics model of lampreys was constructed by adding gender ratio and resource as variables, as follows:

$$\frac{dN}{dt} = rN(1 - \frac{N}{K(A,G)}) - V_{predator}(N, predator) \tag{2}$$

where N is the size of lamprey population, r is the natural growth rate, K (A, G) is the environmental carrying capacity dependent on resource A and genetic factor G, and $V_{predator}$ is the predation rate.

The model can simulate the dynamic changes of lamprey population under different resource conditions, and analyze the impact of sex ratio on population size.

3.1.3 Genetic algorithm modeling

Genetic algorithm is introduced to optimize the model parameters to improve the adaptability and prediction ability of the model. Genetic algorithm is a heuristic search algorithm, which solves the optimization problem by simulating the process of natural selection. The specific model is as follows:

$$G_{new} = \mathrm{var}\,iate(cross(G_1, G_2), V_{\mathrm{var}iate}) \tag{3}$$

where G_{new} represents the genetic factor of the new generation of individuals, variate represents the variation operation of genetic factors, cross represents the cross-recombination operation of genetic factors, and $V_{variate}$ represents the variation rate.

Genetic algorithm can optimize the key parameters in the model, such as the threshold of gender ratio adjustment, resource consumption rate and so on, so as to improve the accuracy and adaptability of the model.

3.1.4 Resource dynamic model

A resource dynamic model was constructed to comprehensively analyze the impact of lamprey sex ratio on ecosystem stability. The model is a continuous dynamic model based on feedback [7], which is used to describe the structure and function of lamprey population. The model considers the population size, resource abundance and other population dynamics of lamprey. The specific model is as follows:

$$\frac{dA}{dt} = r_A A(1 - \frac{A}{E_A}) - consumption(A, N) \tag{4}$$

$$\frac{dN}{dt} = r_N N(1 - \frac{N}{K_A}) - V_{predator}(N, predator) \tag{5}$$

where r_A is the natural growth rate of resources, E_A is the maximum carrying capacity of resources in the environment, consumption is the consumption rate of resources by lampreys, r_N is the natural growth rate of lampreys, K_A is the environmental carrying capacity of lampreys depending on the number of resources, and G is the genetic factor of individual lampreys.

The model can analyze the impact of resource dynamics on lamprey population and ecosystem stability.

3.2. Model solving

In this paper, the above four models are used to model the ecosystem as a graph structure, and the GNN is used to analyze and predict the impact of the change of gender ratio in the ecological network on the stability of the ecosystem. The graph neural network and deep learning prediction model used are introduced below.

3.2.1 Application of graph neural network

In order to further explore the impact of lampreys' sex ratio change on ecosystem stability, this study constructed the ecosystem as a graph structure G= (V, E) with the help of GNN technology. In this structure, the node set V represents different species, and the edge set E depicts the interaction between species, such as predation, competition, etc., and the weight of the edge reflects the intensity of the interaction. GNN updates the representation of nodes by aggregating the characteristic information of their neighbors, so as to capture the complex nonlinear relationships in the network. Specifically, the node update formula of GNN is as follows:

$$h_i^{(l+1)} = \mathrm{Re}\,LU(W^{(l)} \cdot AGGREGATE_{j \in N(i)}(h_j^{(l)}) + b^{(l)}) \tag{6}$$

where $h_i^{(l)}$ represents the eigenvector of node i in layer l, $W^{(l)}$ and $b^{(l)}$ are the weight matrix and offset term of layer L respectively, N(i) represents the set of neighbor nodes of node i, AGGREGATE represents aggregation operation, which usually adopts summation or average.

Through multi-layer iterative updating, GNN can effectively learn the complex dependencies between nodes, and then evaluate the impact of gender ratio changes on the stability of the ecological network. In this study, GNN was used to analyze the effect of the sex ratio of lampreys on the structure and stability of ecosystem network. By constructing an ecological network including lampreys and other related species, GNN can reveal how the change of sex ratio affects the stability of the whole ecosystem through the interaction between species. For example, when the sex ratio of lamprey's changes, GNN can capture the chain reaction of this change on predator and prey populations, as well as the potential impact on the overall structure and function of the ecosystem.

3.2.2 Application of deep learning prediction model

In order to accurately predict the change of sex ratio of lamprey and its impact on ecosystem stability, this study introduced the deep learning prediction model. The model is based on DNN, which can deal with complex nonlinear relationships, thus providing strong support for ecosystem stability analysis. The input characteristics of DNN model include key ecological parameters such as resource availability, current sex ratio and population size, while the output is the change trend of sex ratio and the stability index of ecological network.

The training process of DNN model is as follows: first, collect the historical data set containing the data of lamprey sex ratio change and ecological network stability. Then, the DNN model is trained with these data, and the optimization goal is to minimize the mean square error (MSE) between the predicted value and the actual value. The back propagation algorithm is used to update the model parameters and gradually improve the prediction accuracy of the model. After the training, DNN model can predict the future change of gender ratio and its impact on ecosystem stability based on the current ecological parameters, and provide a scientific basis for ecological management and decision-making.

In this study, the training and verification process of DNN model strictly follows the best practice of machine learning [8]. By dividing the data set into training set, validation set and test set, the model is comprehensively evaluated to ensure its stability and generalization ability on different data subsets. In addition, this study also uses a variety of regularization techniques, such as weight attenuation and dropout, to prevent the model from over fitting and further improve the prediction performance of the model.

3.2.3 Model integration and optimization

In order to improve the accuracy and adaptability of the model prediction, the GNN and DNN are integrated, and the model parameters are optimized by genetic algorithm. Specifically, first, the output results of GNN and DNN are fused to form a comprehensive prediction result. This integration method makes full use of the advantages of the two models. GNN is good at capturing network structure information, while DNN is good at dealing with complex nonlinear relationships. The combination of the two can more comprehensively reflect the impact of gender ratio changes on ecosystem stability.

Then, genetic algorithm is used to optimize the parameters of the integrated model. Genetic algorithm simulates the process of natural selection and uses selection, crossover and mutation operations to gradually search for the optimal solution. In this study, the parameters optimized by genetic algorithm include the threshold of gender ratio adjustment, resource consumption rate and other key ecological parameters. By optimizing these parameters, the model can better adapt to the changes of ecosystem under different environmental conditions, and improve the accuracy and reliability of prediction.

Finally, the optimized integration model is verified by cross validation and actual data testing. The results show that the optimized model performs well in predicting the change of gender ratio and its impact on ecosystem stability, and can provide strong support for ecosystem management and protection.

3.3. Analysis and discussion

3.3.1 Complex network modeling and application of graph neural network

Modeling the ecosystem as a graph structure G= (V, E) is an effective method that can visually represent the complex ecosystem structure and interactions. By representing species as nodes V and interactions between species (such as predation, competition, symbiosis, etc.) as edges E, the dependencies between species and the topological characteristics of the overall network can be captured. This approach allows for a more intuitive understanding of how different species are interconnected and how changes in one species can propagate through the network.

The GNN performs exceptionally well in processing graph data and can learn the complex nonlinear relationships between nodes. This capability is crucial for predicting the impact of gender ratio changes on the stability of ecological networks. GNN dynamically reflects the impact of resource changes on the sex ratio of lampreys by aggregating the characteristic information of node neighbors. For example, when resource availability changes, GNN can predict the adjustment of sex ratio in lamprey populations and evaluate the impact of this adjustment on the stability of the ecological network.

Through the analysis of the graph structure, it is evident that changes in the sex ratio not only affect the internal structure of lamprey populations but also have cascading effects on the stability of the entire ecosystem through species interactions. For instance, a shift in the sex ratio of lampreys can alter the predation dynamics, which in turn affects the population sizes of both predators and prey. This interconnectivity highlights the importance of considering the entire ecological network when assessing the impact of sex ratio changes.

3.3.2 Result analysis of deep learning prediction model

The DNN provides strong support for predicting changes in the sex ratio and their impact on ecosystem stability. The input features of the DNN model include key ecological parameters such as resource availability, current sex ratio, and population size, while the output is the change trend of the sex ratio and the stability index of the ecological network. By training on historical data, the DNN model can learn the complex nonlinear relationships between input features and output results, thereby improving the accuracy of predictions.

In the model training process, the MSE is used as the loss function, and the model parameters are updated using the backpropagation algorithm [9]. The trained model can predict future changes in the sex ratio and their impact on ecosystem stability based on current ecological parameters. For example, the model prediction results show that in resource-rich environments, the sex ratio tends to be balanced, and ecosystem stability is high. In contrast, in resource-deficient environments, the sex ratio tends to be dominated by males, and ecosystem stability is low. This prediction result provides an important scientific basis for the management and protection of ecosystems.

Moreover, the DNN's ability to capture long-term dependencies and automatically extract features from data allows it to handle complex ecological dynamics more effectively than traditional models. This capability is particularly useful in predicting how changes in the sex ratio of lampreys can influence the overall health and stability of the ecosystem over time. The model's predictions can help identify critical thresholds and tipping points in the ecosystem, which are essential for developing proactive management strategies.

3.3.3 Result interpretation of advanced data visualization

Advanced data visualization technology provides an intuitive tool for understanding the impact of gender ratio change on ecosystem stability. Through dynamic graph visualization and interactive exploration [10], the dynamic changes and trends of the ecological network can be clearly displayed. The ecological network visualization of lamprey population dynamics is shown in Figure 1.

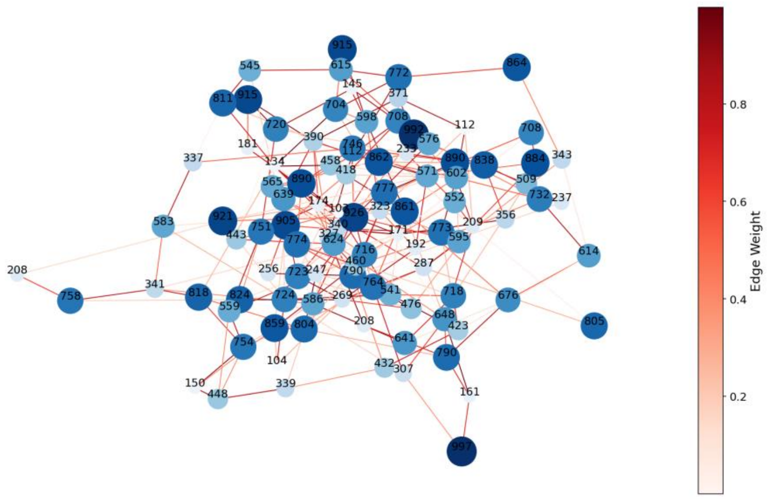

Figure 1. Visual ecological network of lamprey population dynamics

Figure 1 shows the lamprey population and its interaction network with other species in the ecosystem. Each node in the graph represents a species. The size of the node reflects the population size of the species, with larger nodes indicating species with larger population sizes, which may play more important roles in the ecosystem. The color of the node indicates the health status of the population, with darker colors representing healthier populations. This color coding helps to quickly identify which species are in a more stable state in the ecosystem.

The edges in the graph represent the interactions between species, and the thickness and color of the edges represent the intensity and type of interactions. Thicker edges and darker colors indicate strong interactions, which may have a greater impact on the stability of the ecosystem. This visualization clearly shows which species have close interactions, which may be predation, competition, or symbiosis. The close interaction network shows that the dynamic changes among these species may have a chain reaction on the stability of the entire ecosystem.

From the visualization, it is evident that changes in the sex ratio of lamprey populations have a significant impact on the structure and stability of the ecological network [11]. In resource-rich environments, the sex ratio tends to be balanced, the population size is larger, and the ecosystem stability is higher. In resource-deficient environments, the sex ratio tends to be dominated by males, the population size is smaller, and the ecosystem stability is lower. This dynamic adjustment of the sex ratio reflects the adaptability of lamprey populations to resource changes, but it may also affect the population dynamics of other species interacting with lampreys, thereby influencing the stability of the entire ecosystem.

3.3.4 Comprehensive assessment of ecosystem stability

Based on the above analysis, the dynamic adjustment of the sex ratio has a significant impact on ecosystem stability. Through the combination of the GNN and the DNN, the impact of sex ratio changes on the structure and stability of ecological networks can be comprehensively evaluated. Specifically, changes in the sex ratio not only affect the size and health status of lamprey populations but also influence the stability of the entire ecosystem through species interactions. For example, changes in the sex ratio may affect the dynamics of predator and prey populations, thereby impacting the function and stability of ecosystems.

In addition, model integration and optimization enable more accurate predictions of changes in the sex ratio and their impact on ecosystem stability. These prediction results provide important scientific basis for ecosystem management and protection. For example, predicting the impact of sex ratio changes on ecosystem stability allows the formulation of more effective resource management strategies, optimization of resource allocation, and improvement of the ecosystem's adaptability and stability.

Furthermore, the insights gained from this study can be applied to other species and ecosystems, providing a general framework for understanding how population-level changes can influence broader ecological dynamics. This approach can help identify key species and interactions that are critical for maintaining ecosystem stability, thereby guiding conservation efforts and management practices. Future research can build on these findings by exploring additional factors, such as climate change and habitat fragmentation, to further refine our understanding of ecosystem stability and resilience.

4. Conclusions

In this study, a model that fuses graph neural network and deep learning technology was constructed to analyze the impact of lamprey sex ratio dynamics on ecosystem stability, revealing the positive role of sex ratio adjustment in optimizing resource utilization and maintaining ecological balance. The results not only provide a theoretical basis for understanding the ecological regulation mechanism of species, but also provide a new methodological reference for complex ecological network modeling. Although significant results have been achieved, there is still room for improvement in future research, such as extending the model to multi species interaction scenarios, introducing climate change factors and evaluating the adaptability of gender ratio strategies, so as to further improve the accuracy and applicability of the model and provide more comprehensive support for the sustainable management and protection of ecosystems.

References

[1] Zhao Lingling. Sex Ratio Imbalance in Animal Populations and Its Influencing Factors [J]. Animal Husbandry and Feed Science, 2014, No. 5: P80-81.

[2] Feng Yuting, Zhou Caiying, Zhan Xinlong. Research on Aquatic Animal Sex Ratio Variation Based on the Lotka-Volterra Population Dynamics Model [J]. Advances in Applied Mathematics, 2024, Issue 5: P2469-2475.

[3] Wu Cankai. Research on Feature Selection Methods Based on Genetic Algorithm [D]. Wuhan: Huazhong University of Science and Technology, 2024.

[4] Ma Shuai, Liu Jianwei, Zuo Xin. A Survey on Graph Neural Networks[J]. Journal of Computer Research and Development, 2022, Vol. 59(No. 1): P47-80.

[5] Yang Chun, Zhang Ruiyao, Huang Long, et al. A Survey on Quantization Methods for Deep Neural Network Models[J]. Chinese Journal of Engineering, 2023, Vol. 45(No. 10): P1613-1629.

[6] Zhao Qidan. Error Analysis-Based Local Logistics Model and Its Application [D]. Shanxi: Shanxi University, 2024.

[7] Yan Weipo, Guo Yalin, Wang Qing, et al. Theoretical Model and Method for Evaluating Resource and Environmental Carrying Capacity Under Dynamic Supply-Demand Balance [J]. World Sci-Tech R&D, 2023, No. A1: P114-123.

[8] Yu Yueming. Research on Key Technologies of High Robustness Machine Learning [D]. Xi'an: Xidian University, 2024.

[9] Zhang Li, Tian Mi, Li Kai. Optimization of Codonopsis Pilosula Polysaccharide Extraction Process Using Genetic Algorithm Combined with Backpropagation Neural Network [J]. Journal of Food Safety and Quality Inspection, 2020, Vol. 11 (No. 24): P9563-9567.

[10] Tao Jun, Zhang Yu, Chen Qing, et al. Intelligent Visualization and Visual Analytics[J]. Journal of Image and Graphics, 2023, Vol. 28(No. 6): P1909-1926.

[11] Li Zhouyuan, Ye Xiaozhou, Wang Shaopeng. Ecosystem stability and its relationship with biodiversity [J]. Chinese Journal of Plant Ecology, 2021, Vol. 45 (No. 10): P1127-1139.