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Matrix Differential Equation Modeling Of Sex Ratio Change And Multivariable Effect Analysis Of Ecosystem

Feilong Huo[1], Yue Liu[2] , Ruli Zhang[3]
[1,2,3]*(School Of Energy Engineering, Shanxi Institute Of Science And Technology, China)*

Abstract:
Adequacy of food supply has a significant effect on the sex ratio of juvenile sea lampreys, which also adjusts to changes in the external environment, influenced by resource availability, position in the food web, and ecological niche. Therefore, it is necessary to pay attention to the effects of changes in sea lampreys' sex ratio on ecosystem interactions. In this paper, we constructed an ecosystem model. We comprehensively analysed the impacts of sea lamprey's sex ratio changes on the ecosystem from the four dimensions of the logistic equation of the population dynamics model, the sex ratio model, the food web model, and the spatio-temporal model[1,2,3]. The study showed that the sea lampreys population showed adaptability to changes in the environment[4], and its population was affected by ecological niche and resource utilisation; incubation temperature had a significant effect on the sex ratio; the sea lampreys played an important role in the balance between predators and prey; and showed adaptability to the gradient of the environment, suggesting that spatial heterogeneity exists in the ecosystem. The comprehensive assessment showed that the multilevel impacts of the sea lampreys on ecosystems included the regulation of population dynamics, the maintenance of food web balance and adaptation to changes in the environment, thus playing an important role in the stability and functioning of ecosystems.
Key Word*: Sea lampreys sex ratio; ecosystems; population dynamics; space heterogeneity; food web equilibrium*

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I. Introduction

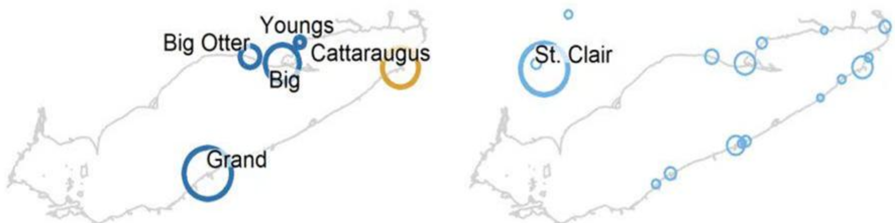
The sea lampreys is a lake- and ocean-inhabiting species whose population sex ratio fluctuates in response to changing conditions in the environment. During its life cycle, especially in the larval stage, sex determination is closely related to food availability[5]. As the environment changes, the population sex ratio of the sea lampreys varies, triggering an in-depth study of its role and impact on the ecosystem[6].This paper aims to understand the potential impacts of dynamic changes in the sex ratio of sea lampreys on ecosystems. This issue cuts across several disciplinary areas, including ecology, behaviour, and evolutionary biology[7]. It requires mathematical modelling to simulate sex-ratio variation and further explore its significance for ecosystem interactions. By delving into this phenomenon of sex ratio variability, we will provide valuable insights into understanding the dynamics of ecosystems[8].

Figure 1 : Detailed geographical distribution of the sea lampreys. they are found on temperate coasts all over the world except Africa, e.g. Scandinavia, and the Baltic region.

Figure 2 (a): Geographical distribution of the sea lampreys.

(b) Distribution of the sea lampreys in the Americas.

(c) Distribution of the sea lampreys in Canada.



(d) Distribution of the sea lampreys in New Zealand.

(e) Assessment of ecosystem impacts.

Figure2: Geographical distribution of the sea lampreys. For the distributional display of the sea lampreys, in North America (Figure 2), they are commonly found in freshwater and coastal areas in the north-east. They can also be found in some rivers and coastal waters in Europe, such as the United Kingdom (Figure 2). sea lampreys are also found in parts of Asia, including the waters of the Russian Far East.

To explore the effects of changes in sea lampreys sex ratio on the ecosystem (Figure2), we analysed the factors influencing changes in sex ratio, including temperature, food availability and environmental conditions. To simplify the problem, we made the following basic assumptions: the model assumes that there is no migration between different populations of sea lampreys and that populations in a given environment are relatively isolated; female and male populations of sea lampreys follow a logistic growth model, respectively, under ideal conditions that are unaffected by the external environment and where there are sufficient resources; individual sea lampreys are assumed to be rational in a game and make decisions based on the maximisation of their own survival and reproductive success; assuming that temperature has a linear effect on the sex ratio of sea lampreys and that the proportion of males may increase and the proportion of females may decrease when the temperature increases, and vice versa.

By examining these aspects, we aim to understand whether changes in the sex ratio of sea lamprey populations can provide an advantage to other species in the ecosystem. Analysing these factors and their effects on sea lamprey populations in combination will enhance our understanding of their ecological role and their wider impacts on ecosystems.

Table 1 : nomenclature

Symbol	Description
r	Growth rate
N	Population size
K	Environmental capacity of ecosystems
P	Sex ratio
dt	Time interval during simulation
α	Rate of change of the sex ratio per unit of time
α_f	Rate of change of the ratio of male to female
α_c	The food contribution of sea lampreys to predators
α_P	Predation rate of sea lamprey
γ_c	Natural predator mortality
D_P	Reflects the spread of sex ratio in space
D_N	Reflect the effect of total population size and sex ratio on birth and death

II. Integrated Analysis Of The Impacts Of The Sea Lampreys Based On An Ecosystem Model

In order to address the research question of the mechanism of the impact of the sea lamprey's sex ratio change on the ecosystem, we focus on the role of the sea lamprey as a keystone species[9] of the ecosystem. By constructing an ecosystem model (Figure 3) that covers multiple dimensions, we aim to delve into the multi-level impacts of changes in the sex ratio on the ecosystem.

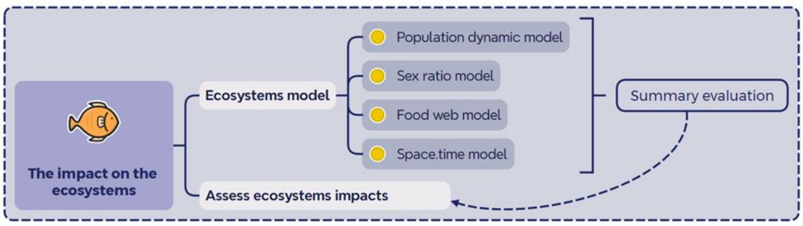


Figure3： Flow chart of our work. Our ecosystem model consists of four main aspects: population dynamics model, sex ratio model, food web model and spatio-temporal model.

The population dynamics model uses logistic equations to describe the growth pattern of sea lamprey populations in different environments; the sex ratio model focuses on the factors affecting the sex ratio, such as temperature and food supply; the food web model focuses on the relationship between predators and prey and their position in the food web; and the spatial-temporal model explores the adaptability of the sea lamprey to the gradient of the environment and the heterogeneity of its spatial distribution. adaptations and the heterogeneity of their spatial distribution.Through the comprehensive assessment of this series of models, we were able to gain a deeper understanding of the complex impacts of changes in the sex ratio of the sea lampreys on the ecosystem (Figure 3). This will not only help to reveal its ecological niche and function in the ecosystem but also provide a scientific basis for ecosystem management to better maintain biodiversity and ecological balance.

III. Modelling And Analysis Of Male And Female Population Dynamics Of The Sea Lampreys

In order to construct the population dynamics model, we introduce the female population dynamics equation[10] and the male population dynamics equation as follows:

$$\frac{dN_f}{dt} = r_f N_f\left(1 - \frac{N_f}{K}\right) - P_f N_m \quad (1)$$

$$\frac{dN_f}{dt} = r_f N_f\left(1 - \frac{N_f}{K}\right) - P_f N_m \quad (2)$$

Where N_f , represents the number of female population, r_f, represents the growth rate of females, P_f, represents the sex ratio of females, N_m , represents the number of the population, r_m , represents the growth rate of males, and P_m , represents the sex ratio of males, which we can get the change of the number of females and males per unit of time by bringing them into the formula.

In the simulation process, we used the Eulerian method to update the number of female and male populations, and the initial conditions were set as the number of female and male populations were each 5, and the sex ratio was 0.5. Simulated maps of female and male population dynamics of the sea lampreys, population dynamics, reproduction strategy, ecological niche distribution, and spatial[11] and temporal distribution were plotted.

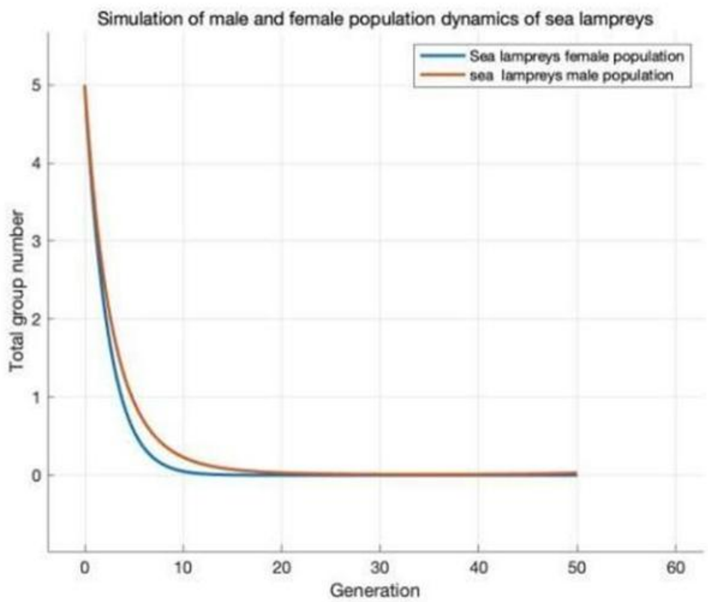


Figure4： Simulation of male and female population dynamics of sea lampreys. By analysing the model of female and male population dynamics of sea lampreys, we can gain insights into the specific impacts of changes in population size over time on ecosystems.

The results showed that female and male populations declined significantly in the initial stage, which may be related to resource competition ,environmental pressure or survival challenges. With time, the population size tends to stabilise, indicating that the sea lamprey population has reached a new equilibrium state after the initial dynamic adjustment.

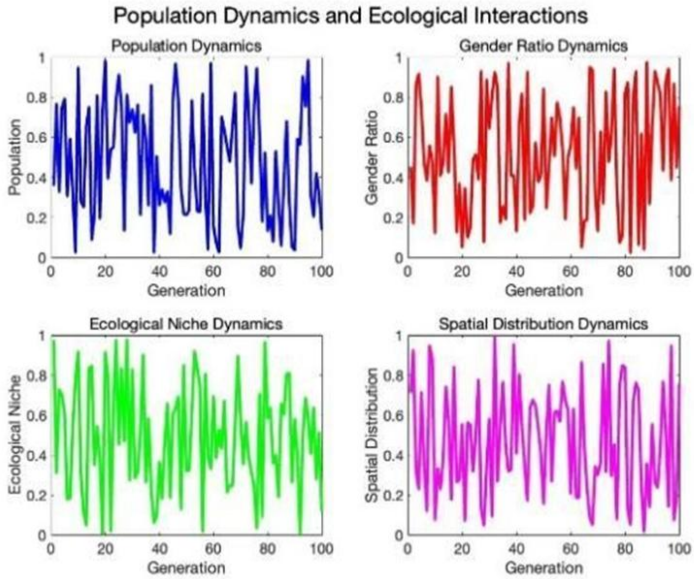


Figure5：Population Dynamics and Ecological Interactions. In the process of generation-by-generation turnover, an in-depth study on the population dynamics of the sea lampreys has concluded that there is an interaction between the dynamics of this population and the ecological environment in which it is located.

Specifically, changes in female and male population size (Figure 4) not only affect the reproductive success of individuals but may also have important implications for energy flow and species interactions throughout the ecosystem. Decreasing population size may lead to changes in the dynamic balance between predators and prey (Figure 4), thus affecting the stability of the entire food chain. Stable population sizes, on the other hand, may help to maintain the structure and function of ecosystems and contribute to the maintenance of species diversity and ecological balance. Through the analysis of this dynamic model (Figure 5), we were able to better predict the performance of sea lampreys under different environmental conditions and provide a scientific basis for related ecological management and conservation strategies.

This analysis revealed the dynamic characteristics of the sea lamprey population at different time stages (Figure 5), providing an in-depth understanding of the population growth pattern and ecological behaviour. These results not only demonstrate the temporal evolution of the population size (Figure 4) but also provide fundamental data for further studies on the ecological niche and reproductive strategies of the sea lamprey. Through this comprehensive analysis, we are able to better understand the adaptation mechanisms of sea lamprey populations under changes in the environment and their impacts on the ecosystem.

IV. Sex Ratio Modelling And Analysis Of The Sea Lampreys

We developed a population dynamics model based on changes in the sex ratio of sea lampreys in response to the external environment (Figure 5) and introduced a sex ratio model to simulate the effect of sex ratio on population dynamics.

$$\frac{dP_t}{dt} = \alpha_f P_t (1 - P_f)(P_m - P_f) \quad (3)$$

$$\frac{dP_m}{dt} = \alpha_m P_t (1 - P_m)(P_f - P_m) \quad (4)$$

Where P_t ,represents the female sex ratio; represents the male sex ratio; P_m , represents the male-to-female ratio change rate, bringing, into the equation, we can get the change in sex ratio per unit of time.

By substituting these variables into the equation[12,13]and solving the differential equation approximately using Euler's method, we can analyse the change in sex ratio per unit of time. At the same time, we considered linear changes in sex ratios to observe trends in the population. The results include a graphical representation of the female and male sex ratio over time (Figure 6), a graph of the overall trend of the sex ratio (Figure 7), a graph[14] of the effect of incubation temperature on the sex ratio (Figure 7), a graph of the change in breeding strategy (Figure 7), and a graph of the effect of ecological niche on the sex ratio (Figure 7). These images demonstrate the effect of changes in the sex ratio of sea lampreys on population structure over a cycle.

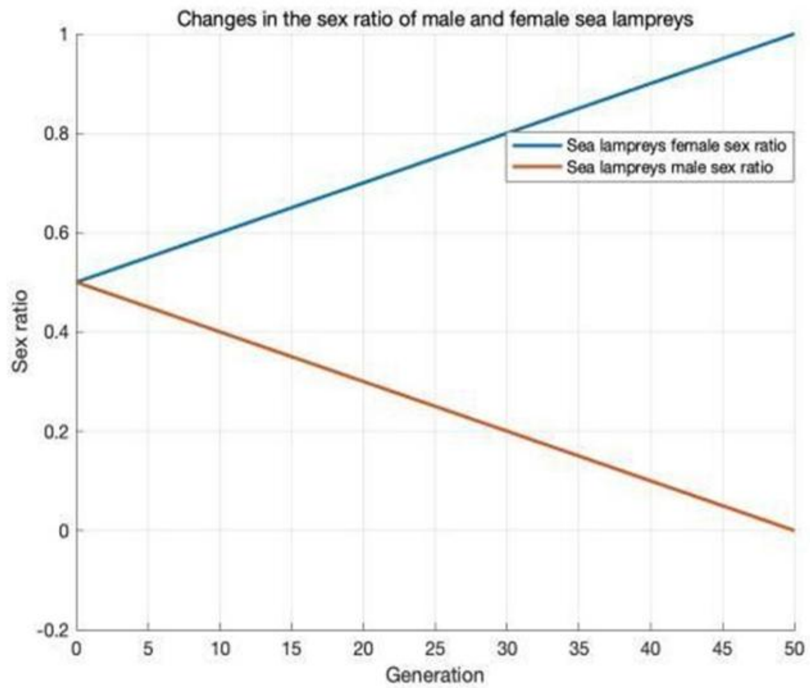


Figure6： Changes in the sex ratio of male and female sea lampreys. In the interaction of ecosystems, the proportion of female sea lampreys gradually increased with each generation, which led to a significant enhancement of the population's reproductive capacity and growth rate.

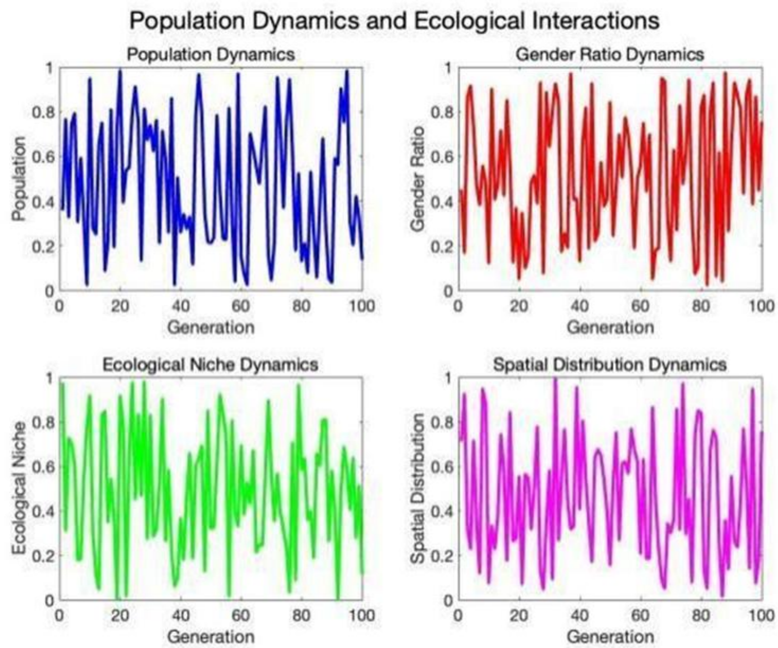


Figure7: Population Dynamics and Ecological Interactions. demonstrates the effects of changes in the sex ratio of sea lampreys on population structure over a cycle.

The analysis of the sex ratio model allowed us to explore in more detail the specific effects of changes in the sex ratio of the sea lampreys (Figure 6) on population dynamics. The results showed that changes in the sex ratio had a significant effect on population structure (Figure 7). In particular, the reproductive capacity and growth rate of the population were enhanced when the proportion of females gradually increased, probably due to the crucial role of females during the breeding season. As the proportion of females increased, reproductive output in the population increased (Figure 6), thus promoting population recovery and expansion. This dynamic is further complicated by the effect of incubation temperature on sex ratios, where changes in temperature lead to skewed sex ratios, thus affecting the long-term stability and resilience of the population. Fluctuations in sex ratios not only altered the population's reproductive strategy but also affected its position and ecological niche in the food web (Figure 7). Changes in sex ratios (Figure 6) may lead to strategic adjustments in resource utilisation and ecological interactions of the population, thus affecting the balance and functioning of the entire ecosystem. This model provides important insights for understanding how sea lampreys optimise their survival strategies under different environmental conditions and also provides a theoretical basis for developing effective ecological management measures and conservation strategies.

The model not only reveals how changes in sex ratio (Figure 6) affect the population dynamics of sea lampreys but also provides a theoretical basis for understanding their ecological adaptations. The results of this study provide valuable references for future ecological studies and population management and help to further explore the ecological behaviours and survival strategies of sea lampreys under different environmental conditions.

V. Modelling And Analysis Of The Food Web Of The Sea Lampreys

In order to gain insight into the position of the sea lampreys in the food web and its potential impact on other species, we constructed a food web model[15] containing equations for prey population dynamics and predator population dynamics.

$$\frac{dN_p}{dt} = r_p N_p \left(1 - \frac{N_p}{K_p}\right) - \beta_p N_p (\alpha_{fp} P_f + \alpha_{mp} P_m)$$
(5)

$$\frac{dN_c}{dt} = r_c N_c \left(1 - \frac{N_p}{K_p}\right) - \beta_p N_p (\alpha_{fc} P_f + \alpha_{mc} P_m) - \gamma_c N_c$$
(6)

Where N_p , represents the prey growth rate; r_p , represents the prey carrying capacity; K_p , represents the predation pressure parameter; β_p , represents the predation rate of the prey by the female sea lampreys; α_{fp} , represents the sex ratio of the females; P_m , represents the predation rate of the male sea lampreys on the prey; and α_{mp} , represents the sex ratio of the males, which is brought into Eq. to get the change of the prey per unit of time.

In the model, A represents the population size of the prey, B represents the growth rate of the prey, C represents the environmental carrying capacity of the prey, D represents the predation pressure parameter, E represents the predation rate of the prey by the female sea lampreys, F represents the proportion of the female sexes, G represents the predation rate of the male sea lampreys on the prey, and H represents the proportion of the males in the sexes. After substituting these parameters into the equation, we can get the variation of prey per unit time.

We used the ode45 function in MATLAB for a numerical solution to analyse the dynamics of population size and sex ratio over time. We plotted the prey and predator population dynamics (Figure 8), species number dynamics (Figure 9), predation relationship (Figure 9), food chain structure (Figure 9) and ecological niche distribution (Figure 9). The results showed that changes in the sex ratio of the sea lampreys population significantly affected the prey and predator populations in the food chain.

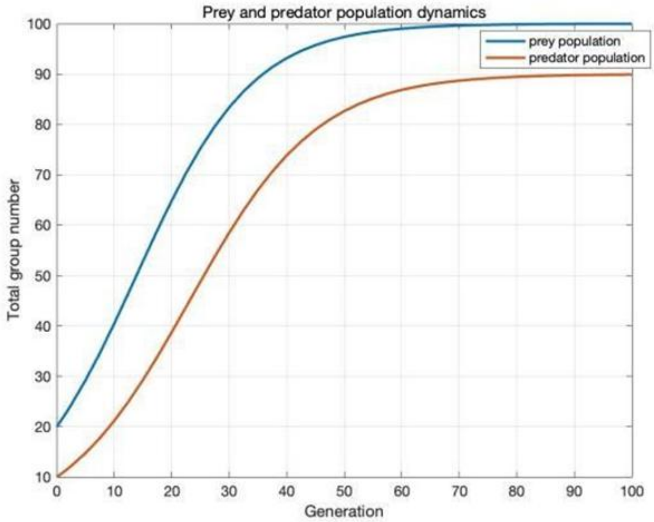


Figure8： population dynamics. we can get the role of the sea lampreys in the food chain and its interrelationships between predators and prey.

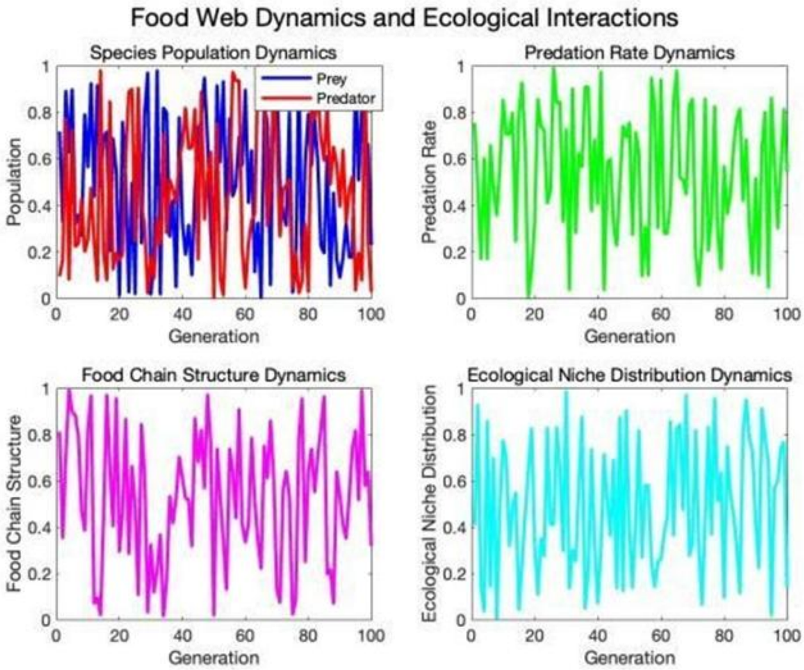


Figure9： Gender Ratio Dynamics and Influencing Factors. Based on the population dynamics, predation relationship, food chain structure, and ecological niche distribution of the sea lampreys, conclusions were drawn about its sex ratio dynamics and influencing factors.

Changes in the sex ratio affect the utilisation of food resources, which in turn affects the consumption of food resources in the overall region. When food is plentiful, the number of females increases, leading to a rise in environmental resources and ultimately an increase in the number of predators. In these graphs, blue dynamic lines are used to represent prey, while red dynamic lines represent predators[16].

By analysing the food web model, we can explore in more depth the specific effects of changes in the sex ratio of sea lampreys on the ecosystem. The results show that changes in predation rates of female and male sea lampreys directly affect the abundance and growth dynamics of prey populations (Figure 8). Specifically, when the proportion of females increased, their higher predation rates led to a significant decrease in prey populations, thus reducing the competitive pressure between predators and leading to an increase in predator populations (Figure 8). Conversely, when the proportion of males increases, the prey population increases relatively due to their lower predation rate (Figure 8), which may have a suppressive effect on the predator population. Such dynamic changes not only alter the population structure of the sea lampreys itself but also affect the energy flow and interactions between species throughout the food web. Through this modelling analysis, we are able to predict the long-term effects of sex ratio changes on the food chain[17]structure and stability under different environmental conditions, providing theoretical support for the conservation and management of ecosystems (Figure 9).

Modelling the food web enabled us to gain a comprehensive understanding of the impacts of changes in the sex ratio of sea lamprey populations on the ecosystem as a whole, and to gain a deeper understanding of the dynamic relationships between components within the ecosystem. Through this model, we can speculate on the effects of sex ratio changes on the structure and stability of the food chain, providing a scientific basis for ecosystem management and conservation strategies.

VI. Spatial And Temporal Modelling And Analysis Of The Sea Lamprey

In order to fully understand the adaptation of the sea lampreys to environmental gradients and their distribution in the ecosystem, we constructed a spatio-temporal model[18]. First, we defined key variables: sex ratio (P) and total population size (N).

$$\frac{\partial P}{\partial t} = D_p \nabla^2 P + R(N, P)$$
(7)
$$\frac{\partial P}{\partial t} = D_N \nabla^2 N + B(N, P)$$
(8)

Where the sex ratio P, is assumed to be affected by the diffusion and response terms R(N, P), and the total population size N, is assumed to be affected by the diffusion and birth-mortality terms B(N, P).

By solving the model numerically using the ordinary differential equation solver in numerical methods, we observed the evolution of sex ratio and total population size in space and time. Focusing on the effects of the dispersal term, the birth mortality term and the response term on the population dynamics of the sea lamprey, we plotted a surface map of the sea lamprey sex ratio (Figure 10), a surface map of the total population size (Figure 11), a population distribution map (Figure 12), a distribution map of the sex ratio (Figure 12), a distribution map of the ecological niches (Figure 12), and a spatio-temporal interaction map (Figure 12).

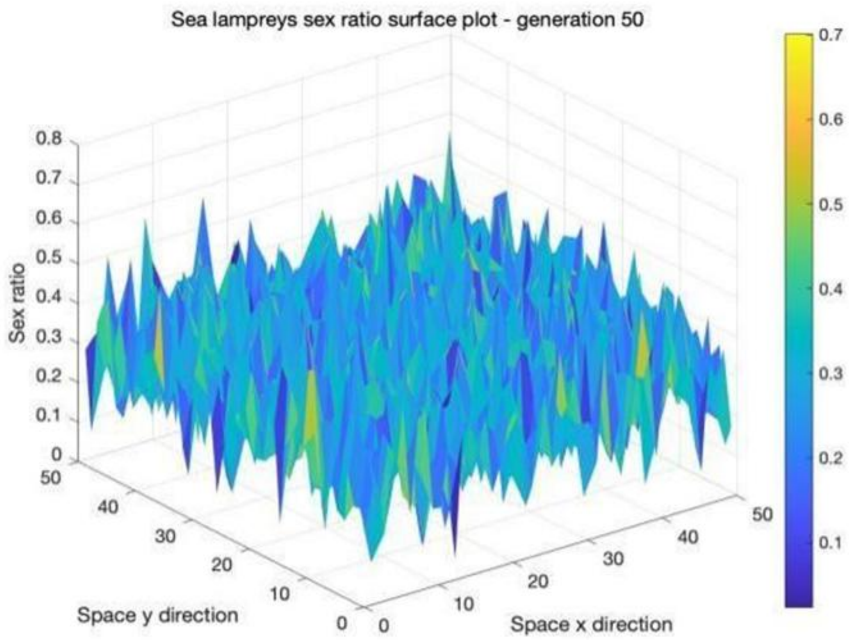


Figure10： Sea lampreys sex ratio. based on 50 generations of spatial X-direction and spatial Y-direction fitting formation.

The dark blue area indicates that the sea lampreys' sex ratio is not balanced, while the yellow area indicates that sea lampreys' sex ratio is balanced.

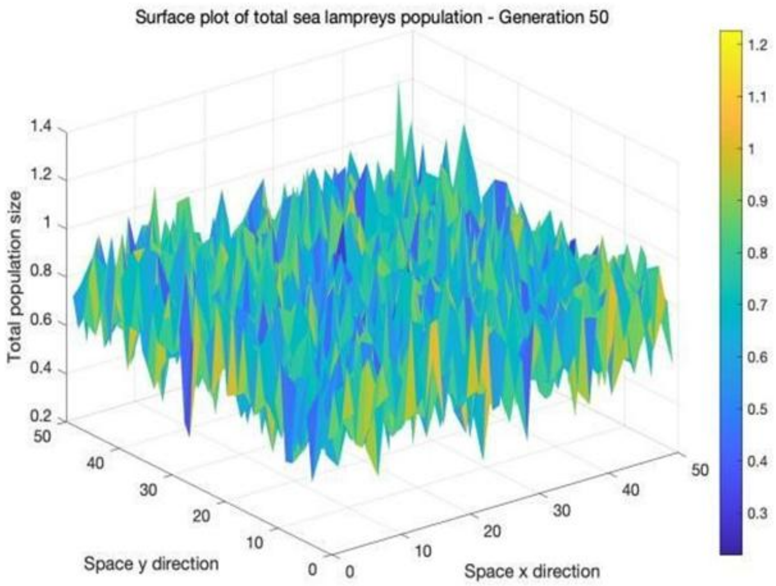


Figure11： total sea lampreys population. The dark blue area indicates that the population of sea lampreys is large, while the yellow area indicates that the population of sea lampreys is small.

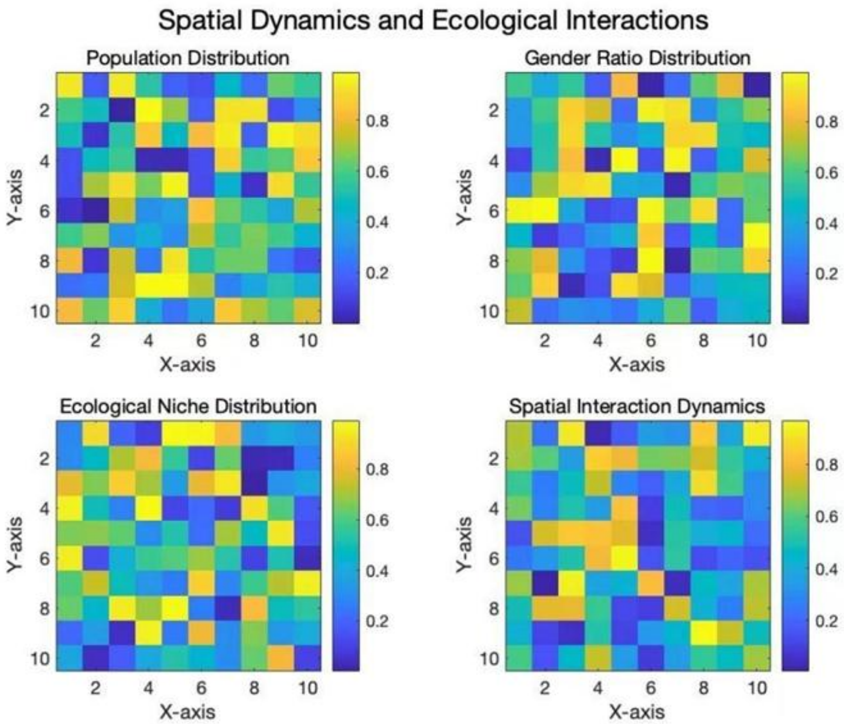


Figure12： Spatial Dynamics and Ecological Interactions. Based on sea lampreys population distribution maps, sex ratio distribution maps, ecological niche distribution maps, and spatial-temporal interaction map fitting provide us with information on the spatial distribution and evolution of sea lampreys.

By analysing the spatio-temporal model, we were able to explore in more detail the adaptations of the sea lampreys under different gradients of the environment and their specific impacts on the ecosystem. The results of the modelling showed that changes in the sex ratio had a significant effect (Figure 10) on the spatial distribution and dynamics of the population (Figure 11). The spatial and temporal distributions of sex ratios and total population size showed significant heterogeneity when environmental conditions changed (Figure 10) (Figure 11). For example, in resource-rich regions, the proportion of females increases, which leads to a significant increase in population size in that region, while in resource-poor regions, the proportion of males may be higher and the population size relatively lower. This difference in spatial and temporal distribution not only affects the survival and reproductive strategies of the sea lampreys itself but also has far-reaching effects on the structure and function of the ecosystems in which it is found. The dynamics of sex ratios alter energy flow and species interactions throughout the food chain by affecting population dispersal and ecological niche occupancy (Figure 12). This model provides an important theoretical basis for understanding the behaviour of sea lampreys at different spatial and temporal scales (Figure 12), as well as scientific support for the development of effective ecosystem management and conservation strategies.

The establishment of spatial and temporal models not only demonstrated the adaptive behaviours of sea lampreys in different regions but also revealed how changes in sex ratios (Figure 10) affect the structure and function of the entire food chain through dispersal and ecological niche occupancy. This study provides an important theoretical basis for understanding the ecological adaptive strategies of sea lampreys and provides a scientific basis for the development of ecosystem management and conservation strategies. Through this integrated spatial and temporal analysis, we are able to better predict and respond to the complex biological dynamics in ecosystems, providing valuable references for future research and practice.

VII. Integrated Assessment Of Ecosystem Models And Summary Of Findings

By constructing an ecosystem model, including a population dynamics model, a sex ratio model, a food web model and a spatial-temporal model, we have comprehensively analysed and assessed the impacts of changes in the sex ratio of the sea lampreys on the ecosystem.

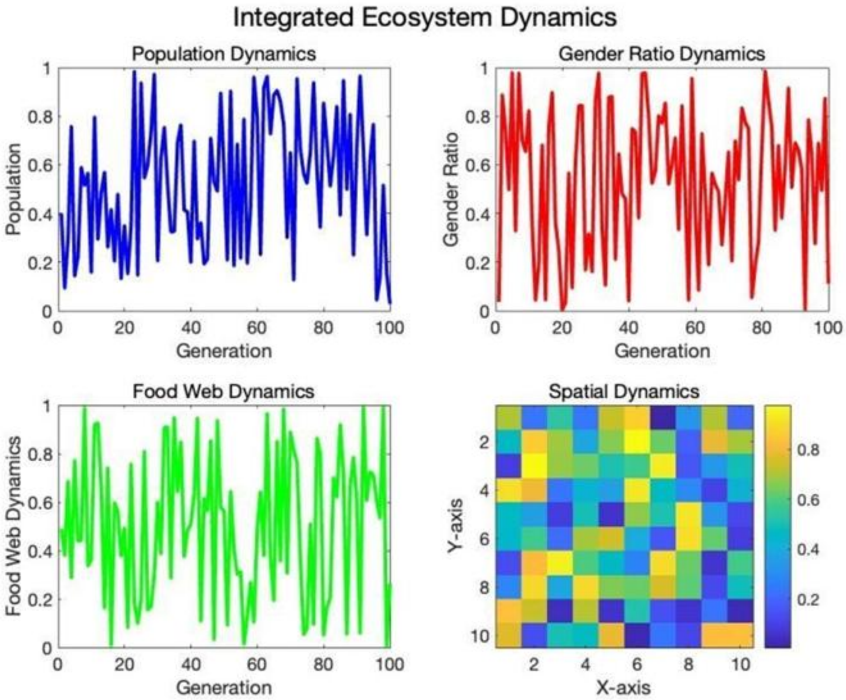


Figure13: Integrated Ecosystem Dynamics. The effects of changes in population dynamics, sex ratio, food web dynamics, and spatial dynamics were fitted to the integrated ecosystem dynamics of the sea lampreys.

Population dynamics modelling

We revealed the trend of population evolution of the sea lampreys in the ecosystem through population dynamics modelling. The results showed that the sea lamprey population showed significant adaptation to changes in the environment (Figure 5), and its population was significantly affected by the ecological niche and resource utilisation of different species (Figure 4). When resources are abundant, sea lamprey populations grow rapidly, and when resources are limited and competition occurs among sea lampreys, populations decline significantly (Figure 4). The interaction between ecological niches and resources determines the dynamics of sea lamprey populations, and such changes are important drivers of ecosystem balance and evolution.

Sex ratio model

The study of the sex ratio model revealed the changing law of the sex ratio of sea lampreys under different environmental conditions (Figure 7), especially the effect of incubation temperature on the sex ratio showed significant adaptability. The results showed that higher incubation temperatures tended to lead to an increase in the proportion of males, while lower temperatures favoured the production of females (Figure 6). This change in sex ratio allows the sea lampreys to adapt to environmental changes to a certain extent, thus ensuring reproductive success and genetic diversity. In warmer environments, the increase in males favours population dispersal and competition, thus affecting population stability and reproductive efficiency. At the same time, changes in sex ratio may also have knock-on effects on the ecosystem's reproductive and food chains, e.g. by altering predation pressure and resource allocation patterns.

Food Web Modelling

Food web modelling provides a deeper understanding of the position and interrelationships of the sea lampreys in the ecosystem. Through its position in the food web, we find that the sea lampreys play an important role in the balance and coordination between predators and prey (Figure 8). Specifically, changes in the predatory behaviour and sex ratio of sea lampreys can significantly affect the abundance and dynamics of prey and predator populations (Figure 9). When the proportion of females is high, their predation rate on prey increases, which may lead to a decline in prey populations (Figure 8), which in turn affects predator abundance and survival. This chain reaction may lead to the reorganisation of food webs and challenges to the stability of ecosystems.

Spatio-temporal modelling

The spatio-temporal model revealed the spatial distribution and migration patterns of sea lampreys. The results showed that there may be significant differences in the abundance and sex ratio of sea lampreys (Figure 10) in different geographical locations (Figure 11). In resource-rich areas, the population size and female proportion of sea lampreys were higher, while in resource-poor areas, the population size and male proportion were higher (Figure 12). This suggests that sea lampreys are adapted to the environmental gradient, creating differences in resource use, and suggests that spatial heterogeneity exists in ecosystems (Figure 12). In addition, the spatio-temporal modelling demonstrated the ecological adaptations of the sea lampreys to different seasonal and environmental conditions for food resources in different geographical locations.

Summary of the Impact Assessment

Ecosystem stability: Modelling of population dynamics has shown that the adaptation of the sea lampreys to the environment improves the overall stability of the ecosystem. Interrelationships between populations such as competition and parasitism also affect their numbers and densities, and the balance and co-ordination of these interactions help to maintain the stability of the ecosystem. When resources are sufficient, population size increases, which helps to maintain the balance of the ecosystem; while when resources are scarce, population size decreases, which may lead to instability of the ecosystem. When the sea lampreys adapt to and rationally utilise their ecological niche, it promotes the effective use of resources, which in turn increases the stability of the ecosystem.

Reproductive strategies: Sex ratio modelling reveals the sex ratio regulation mechanism of the sea lamprey, which has important implications for reproductive strategies and the genetic diversity of a species that is highly influenced by environmental factors. In the face of climate change, sex ratios were adjusted to alter reproductive strategies to adapt to different environmental conditions. In warm environments, an increase in the male ratio may favour population competitiveness and genetic diversity, while in cold environments, an increase in the female ratio may favour the reproductive success of the population, reducing reproductive inputs and ensuring population survival.

Food chain impacts: According to the food web model, the role of sea lampreys in the food chain has multiple impacts on the structure and stability of the entire food web. Sex ratio imbalance affects the reproductive success and population size of the species, leading to a decrease in the number of predators at the level of the food chain, which in turn reduces the resources of the consumers at the higher level of the food chain that depends on them for food, affecting their survival and reproduction, and consequently affecting the equilibrium of the food chain as a whole.

Spatial heterogeneity: The spatio-temporal model emphasises the spatial adaptability and distributional heterogeneity of the sea lampreys. This suggests that species face different choices in different geographic locations in different spatially heterogeneous environments, which drives the adaptive evolution of sea lampreys, enabling them to better adapt to specific habitat conditions and increasing species richness. By analysing the distribution of populations in different regions and seasons, where different species occupy different ecological niches and interspecific competition is reduced, we can better understand the ecological adaptations of the sea lamprey, thus providing a scientific basis for ecological conservation and resource management, which is conducive to the coexistence of species and the stability of ecosystems.

Combining the results of the above models, we have gained an in-depth understanding of the multi-level impacts of the sea lamprey on the ecosystem, providing a useful scientific reference for the conservation and management of this species. This series of models and analyses provides a systematic approach and theoretical basis for our understanding of key species dynamics in complex ecosystems, which will help future applications in ecological research and environmental management.

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