Mathematical Modeling and Algorithm Application
ISSN: 3006-0842 | Vol. 5, No. 2, 2025

Research on System Hierarchy Interaction Mechanisms and Self-Regulation Potential Based on Logistic Growth Model and Lotka-Volterra Model

Yizun Zhou*, Yuanyuan Zhang

[1]School of Intelligent and Electronic Engineering, Dalian Neusoft University of Information, Dalian, China

* **Corresponding author**: Yizun Zhou(Email: zzyz0546@163.com)

Abstract: This paper constructs a multi-model system centred on the Logistic growth model and the Lotka-Volterra model to systematically analyse the evolutionary mechanisms and sustainable regulatory pathways. Firstly, based on a hierarchical interaction model, the study combines the Logistic growth model and the Lotka-Volterra model to analyse the impact of external intervention factors on each hierarchical level, revealing their mechanisms of action through disrupting energy transfer between hierarchical levels and breaking the system's steady state. Subsequently, the study explores different hierarchical introduction scenarios, through model adjustments and simulation validation, their regulatory effects on target variables and system equilibrium are examined. Finally, a non-intervention stabilisation model is constructed, and an optimised Lotka-Volterra model is used to demonstrate that the system can achieve equilibrium through self-regulation, emphasising the importance of enhancing system resilience. This provides a theoretical basis for reducing reliance on external interventions and rebuilding sustainable systems through functional introductions and cyclical patterns.

Keywords: Logistic Growth Model, Lotka-Volterra Model, Chemical Intervention, Ecosystem.

1. Introduction

In the field of complex systems research, how to leverage scientific modelling to analyse the evolutionary patterns of systems and establish sustainable regulatory pathways is a core challenge that the academic community urgently needs to address [1]. In light of this, this study constructs a multi-model system centred on the Logistic growth model and the Lotka-Volterra model, coupling hierarchical interactive relationships to systematically explore the dynamic mechanisms of variables under artificial intervention scenarios and the self-regulatory potential under non-intervention conditions [2]. The study first uses the Logistic model to characterize the growth constraints of basic variables and environmental carrying capacity constraints, and combines the Lotka-Volterra model to analyse the bidirectional interactions between hierarchical levels, quantifying the blocking effects of external intervention factors [3-4]. It then simulates different hierarchical intervention scenarios through model corrections to validate the regulatory efficacy of intervention strategies on target variables and system balance. Finally, by optimising the Lotka-Volterra model, a stabilisation scenario without intervention is constructed to reveal the intrinsic logic of the system's self-regulation [5]. This study aims to break through the traditional management paradigm reliant on external intervention, providing a theoretical framework and methodological support for enhancing the resilience of artificial systems and constructing sustainable management models through model-driven mechanism analysis.

2. Present ecological interaction model

This paper established a model to reflect the process of afforestation and cultivation, focusing on four objects: plants (divided into forest plants and agricultural plants), animal pesticides (this paper assume that herbicides directly affect plant growth, leading to plant death and thereby reducing the number of insects), and natural factors (which directly kill plants and animals). According to these models, the aim was to reflect the change in the total quantity of plants and the curve changes of forest plants and agricultural plants.

For each object, this paper established specific indicators and then found the most suitable values. This paper took Brazil as an example and constructed two indicators for its plants: agricultural plants and forest plants. Figure 1 clearly shows the changes in these two regions in different years. The forest area data increased year by year from 4,966,196 in 2000 to 5,510,886 in 2020, while the agricultural area data decreased year by year from 2,368,788 in 2000 to 2,283,235 in 2020.

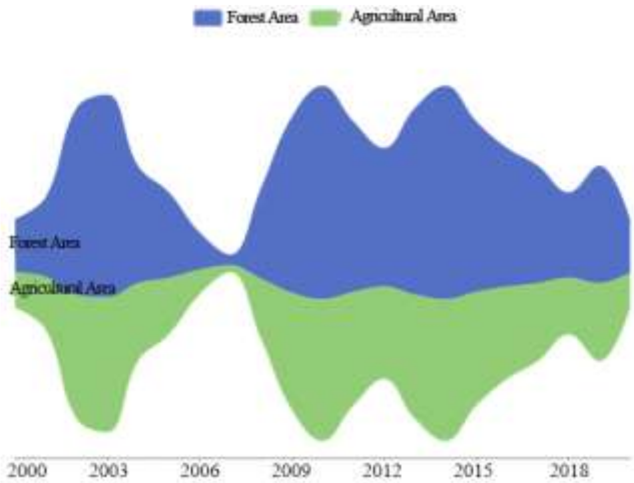

Figure 1. Forest Area vs Agricultural Area

2.1. Food chain model

As the land began to change—soils that were once rich in natural resources became poor—pests began to invade crops. In response, farmers turned to chemicals, but the balance of the land was upset. With this change, the complex web of life that once flourished in the forest was broken, and a new, human-driven ecosystem took its place. To achieve a mature agricultural system, the ecosystem needs to mature gradually.

In this newly established ecosystem, this paper can construct a food chain model to describe the interactions and energy transfer between different species. The food chain model includes the following levels:

(1) Producers (agricultural plants and forest plants)

This paper regarded the relationship between forest plants and agricultural plants as a competitive relationship between producers. There is competition for resources and space between forest plants and agricultural plants, which compete for nutrients, water, and light in the soil. Plants in farmland often require manmade fertilization and irrigation to meet their growth needs, while in natural forests, plants rely on natural conditions for these resources. As forests gradually become farmland, resources originally belonging to forest plants may be used by agricultural plants, resulting in a decrease in forest plant resources. Specifically, these plants belong to the primary producers in the ecosystem, that is, the organisms that convert solar energy into chemical energy through photosynthesis, providing the basic energy source for the entire food web.

(2) Primary consumers (herbivorous insects)

Herbivorous insects such as aphids, caterpillars, and locusts feed on the leaves, stems, roots, etc., and consume the organic matter of the plants. They live directly on the organic matter provided by producers and transfer plant energy to higher trophic levels.

(3) Secondary consumers (predatory insects, birds)

Predatory insects such as ladybugs, praying mantises, and spiders prey on herbivorous insects, helping to control herbivorous insect populations and prevent them from causing excessive damage to plants. Small birds such as sparrows, swallows, and woodpeckers feed on herbivorous insects, maintaining their own energy requirements while also helping to control insect populations.

(4) Top predators (bats, birds, etc.)

Bats, including vampire bats, prey on nocturnal insects such as moths and mosquitoes, helping to control insect populations. Large birds, such as eagles and owls, feed on predatory insects and small mammals to maintain their own energy requirements while also helping to control the numbers of other secondary consumers.

In this food chain model, various levels interact with each other through predator-prey relationships to form a complex food web. The producers provide energy through photosynthesis, the primary consumers feed on the producers, the secondary consumers feed on the primary consumers, and the top predators feed on the secondary consumers. Through these interactions, energy and matter in the ecosystem are recycled and transferred, maintaining the stability and balance of the ecosystem.

In addition to the internal effects of the biological chain, this paper also added two external effects: chemicals and natural disasters.

(1) Effects of chemicals: Herbicides directly affect the growth of plants, resulting in plant death, thereby reducing the food source for primary consumers (herbivorous insects). Pesticides directly affect insect populations, causing insect deaths and thus affecting food sources for secondary consumers and top predators.

(2) Impact of natural disasters: Natural disasters (e.g., floods, droughts, storms, etc.) have a direct impact on all levels of the ecosystem, disrupting its balance.

2.2. Logistic growth model

For the producers in the model, namely forest plants and agricultural plants, the Logistic growth model is mainly used to describe:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) \tag{1}$$

Where $(1 - \frac{N}{K})$ represneted as N approaches K, the value of the regulator decreases gradually, thus easing the growth rate of the population. When it is the same, the population stopped growing.

In order to reflect the land change situation of forest and cultivated land, which is the key relationship, this paper converted the population number into plant area conversion factor in the model calculation, which can ensure the universality of the model.

The relationship between the population number and area of forest plants:

$$N_f = K_f * A_f \tag{2}$$

Where N_f represented the population of forest plants, K_f represented the number of forest plants per square meter and A_f represented forest area.

The relationship between the population size and the area of agricultural plants:

$$N_a = K_a * A_a \tag{3}$$

Where N_a represented the population of agricultural plants, K_a represented the number of farm plants per square meter and A_a represented agricultural area.

Through this simple transformation, this paper can cleverly transform the dependent variable of this model into the plant area.

Consider the effects of pesticides, insecticides, and natural disasters:

$$N(t) = \frac{K}{1+e^{-r*(t-t_0)}} * e^{-d*t} \tag{4}$$

Where $N(t)$ represented population size at time t, r represented the maximum rate at which a population can grow without resource constraints, t_0 represented the time point when the population reached $K/2$, that is, the time when the population reached half of the environmental carrying capacity and d represented the influence coefficient of external factors indicates the inhibitory effect of factors such as pesticides, insecticided and natural disasters on population growth.

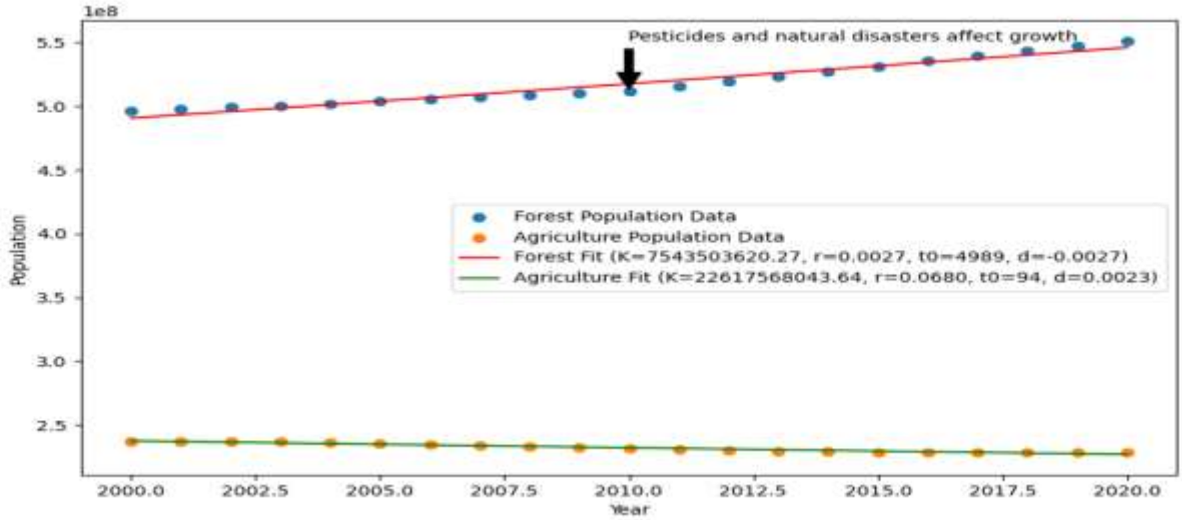

Figure 2. Logistic growth model for forest and agriculture plants with pesticides and natural disasters

As shown in Figure 2, this paper successfully simulated the population changes of forest plants and agricultural plants from 2000 to 2020, and took into account the effects of pesticides, insecticides and natural disasters on the growth of these aggregate populations. The model not only helps us understand the dynamics over different time periods.

2.3. Predator-prey model

The Lotka-Volterra model was used to define the rules of predator and prey population changes. As shown in Figure 3, this model primarily expresses the relationship between producers and consumers, aiming to highlight the dynamics of predation and prey. In the previous model, this paper discussed the relationships among different levels of the biological chain, including internal population growth and competition among producers. The growth relationships over different time periods were constructed based on the Logistic growth model.

To emphasize predation in this model, external factors such as pesticides, which cause a decrease in animal populations, were considered. In the previous model, this paper converted the number of producers by a coefficient ratio, i.e., the number of insects that would have died due to factors such as pesticides was translated into the number of producers that are prey. In this model, these factors will be directly reflected in the calculation formula.

For producers (crops):

$$\frac{dC}{dt} = r_C C\left(1-\frac{C}{K}\right) - \alpha CI - \tau_C \tag{5}$$

Where C represents the quantity of crops, r_C represents the crop growth rate affected by time and season, α represents the efficiency coefficient of insect feeding and τ_C represents the number of herbicides that kill or inhibit the growth of crops.

For primary consumers (herbivorous insects):

$$\frac{dI}{dt} = \beta CI - m_I I - \tau_I - \tau_H BI \tag{6}$$

Where β represented energy transfer efficiency between the first and second trophic stages, m_I represented the natural disaster death and natural mortality, τ_I represented the number of insect deaths caused by pesticides.

For secondary consumers (predatory animal collections):

$$\frac{dB}{dt} = r_B B\left(1-\frac{B}{K}\right) - m_B B - \tau_P BI \tag{7}$$

Where B represented the number of birds, r_B represented the bird's maximum growth rate, K represents environmental maximum carrying capacity, m_B represented natural mortality of birds and τ_P represented the negative impact of insects on birds indicated the impact of reduced insect numbers on the survival of birds.

Consider agricultural cycles and seasonal influences. Through actual life, crops must have a process in the four seasons of growth speed, sometimes the growth rate is slow, this paper used the sine function to simulate this cycle transformation:

$$r_C(t) = r_{C0} + A_C \sin\left(\omega t + \phi_C\right) \tag{8}$$

$$m_I(t) = m_{I0} + A_I \sin\left(\omega t + \phi_I\right) \tag{9}$$

Where r_{C0} and m_{I0} represented the underlying growth rate and the mortality rate, A_C and A_I represent the amplitude indicating the intensity of seasonal fluctuations, and ϕ_C and ϕ_I represent the phase Angle indicating the starting point of the seasonal change.

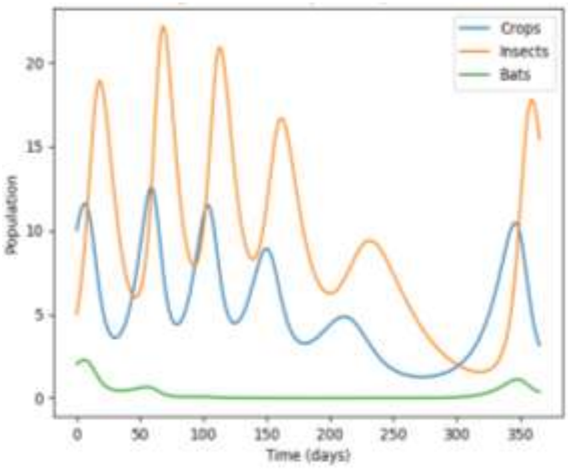

Figure 3. Dynamics of agricultural ecosystems simulated by the Lotka-Volterra model (including chemical interventions)

3. Simulation of species reintroduction interventions in ecosystems

This section actually considered the situation where partial reforestation begins now and new species were introduced into the current ecosystem. Through these newly introduced species, the impact on the ecosystem is to be explored. Let's assume that the original animal species is species A, and the newly introduced species are species B and species C. This paper tried to explore the relationship between A and B, C, and their impact. This paper discussed species B and species C separately. A represents the current ecological population.

(1) The first case

Species B is a pollinator (such as bees that can pollinate), and species C is a disruptor (snakes, frogs can bring benefits to the restoration of the ecological environment), and also serves as food at the highest trophic level.

(2) The second case

Species B is still a pollinator (such as bees that can pollinate), and species C is a top predator. When introduced into the food chain, it can exist at the highest trophic level (such as large predators).

3.1. Intermediate trophic level reintroduction model

This model was an improved competitor model after the addition of species B and C to the predator model. The main function of this model was to feedback various interactions after the addition of new species to the food chain, and the specific results are shown in Figure 4.

Bees increase the growth rate of crops through pollination, and crops also serve as a food resource for bees. Snakes and frogs are used to catch insects and also serve as the highest nutrient level food resources in the original food chain

The effect of the two new species on the original food chain is shown in the equation below:

$$\frac{dC}{dt} = r_C C\left(1 - \frac{C}{K}\right) - \alpha CI - \tau_C + \delta_C H \tag{10}$$

$$\frac{dI}{dt} = \beta CI - m_I I - \tau_I - \tau_H BI - \delta_I SI \tag{11}$$

$$\frac{dB}{dt} = r_B B\left(1 - \frac{B}{K}\right) - m_B B - \tau_P BI \tag{12}$$

The following equation described the population dynamics of bees. Changes in bee populations directly affect crop growth rates:

$$\frac{dH}{dt} = r_H H\left(1 - \frac{H}{K}\right) - m_H H \tag{13}$$

Snake and frog:

$$\frac{dS}{dt} = r_S S\left(1 - \frac{S}{K}\right) - m_S S \tag{14}$$

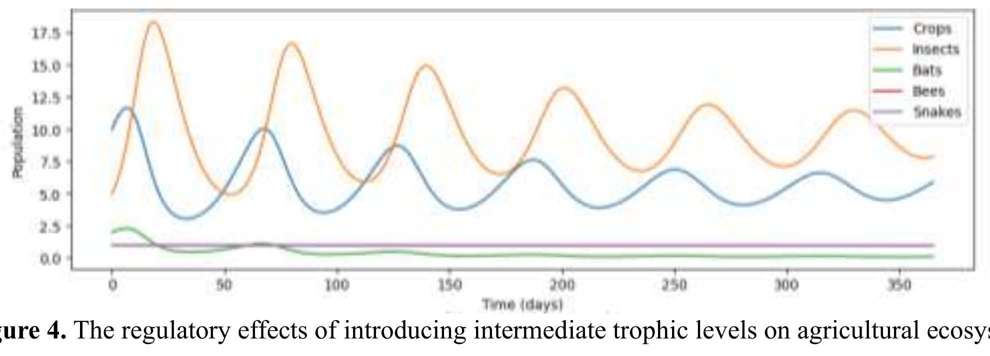

Figure 4. The regulatory effects of introducing intermediate trophic levels on agricultural ecosystems

3.2. Top trophic level reintroduction model

In this discussion we introduced species C as a large raptor into an original ecosystem where it acts as the highest consumer, and the specific results are shown in Figure 5.

Crop growth models whose growth rates are positively affected by bee pollination:

$$\frac{dC}{dt}=r_C C\left(1-\frac{C}{K}\right)-\alpha_C IC-\delta_C HC+\beta_H H \tag{15}$$

Primary consumers, including native insects and newly added species of bees:

$$\frac{dI}{dt}=r_I I\left(1-\frac{I}{K_I}\right)-\alpha_I SI-\delta_I BI \tag{16}$$

Growth model of secondary consumers:

$$\frac{dS}{dt}=r_S S\left(1-\frac{S}{K_S}\right)-\alpha_S RS \tag{17}$$

Large birds of prey on secondary consumers as top consumers:

$$\frac{dR}{dt}=r_R R\left(1-\frac{R}{K_R}\right) \tag{18}$$

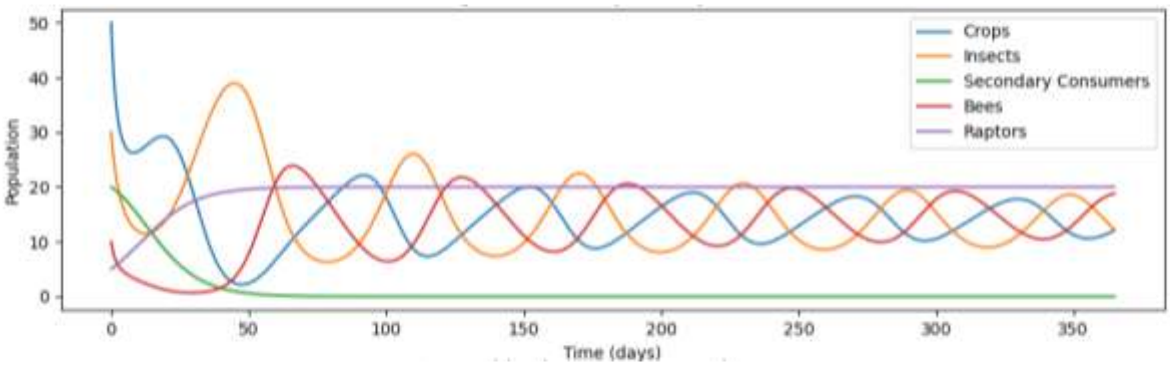

Figure 5. The regulatory effects of introducing top predators on agricultural ecosystems

4. Ecosystem stabilisation: removing the long-term effects of chemical interventions

As shown in Figure 6, after the removal of herbicides and pesticides, the population dynamics of plants and insects in the ecosystem change significantly. Initially, the populations experience a noticeable fluctuation, but after a certain period, the entire ecosystem will begin to trend towards a stable state. It has been confirmed that ecosystems can achieve dynamic balance through natural regulation and the introduction of functional biological groups, highlighting the key role of biodiversity in enhancing ecological resilience.

The model adopts the optimized Lotka-Volterra model, which includes bats as decomposers in addition to the previous components. Bees are included in the ecosystem as both pollinators and primary consumers.

$$\frac{dC}{dt}=r_C C\left(1-\frac{C}{K_C}\right)S_C-\alpha_C IC-\tau_D D+\beta_B B \tag{19}$$

$$\frac{dD}{dt}=r_D D\left(1-\frac{D}{K_D}\right)*S_D \tag{20}$$

The dynamic equation of crop and the dynamic equation of resolver were shown. For the growth of plants and animals, we mainly improved and limit the growth of animals and plants under the logistic model. By setting the maximum environmental capacity, we ensured that species will not increase without limit and maintain the resource balance of the ecosystem.

Secondly, we add seasonal influence, S_C, S_D reflects the influence of different seasons on decomposers. Through the predation term and the positive influence term, the interaction between different species is simulated to form a dynamic balance.

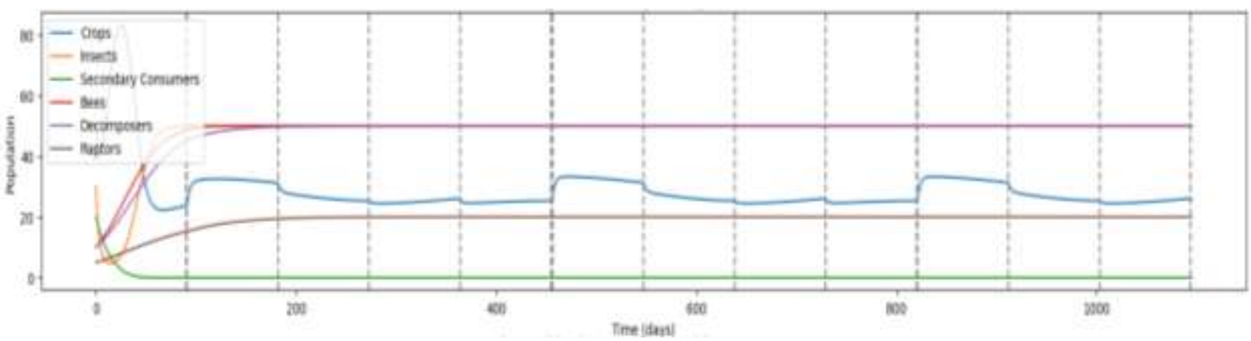

Figure 6. Dynamics of agricultural ecosystems after removal of chemical interventions

This paper explored the interactions between plants and animals and to measure the impact of species diversity, and worked in several directions.

The biodiversity in agricultural ecosystem has been protected, and the stability of the ecosystem has been improved. And it is well known that farms that rely too much on pesticide control often lack a lot of stability. On the one hand, pesticides will reduce some specific species in the population; on the other hand, they will increase the resistance of animals and plants, resulting in poor harvests in the next year and the emergence of various diseases.

Secondly, for the whole ecosystem, it gets a good cycle. The decomposing organic matter is decomposed into nutrients, which are partially digested by the decomposing agent itself and partially reabsorbed by the producer, forming a nutrient cycle. This can carry out a complete ecological cycle, which will enhance the vitality of the soil, help the growth of producers, and provide a good habitat for some consumers.

5. Conclusions

This study establishes a multi-model system centred on the Logistic growth model and the Lotka-Volterra model to analyse the evolutionary mechanisms and sustainable regulatory pathways associated with changes in system structure and function. First, based on a hierarchical interaction model, the Logistic growth model and the Lotka-Volterra model are combined to analyse the impact of external intervention factors on each hierarchical level. Subsequently, different hierarchical intervention scenarios are explored, and through model refinement and simulation validation, the regulatory effects of such strategies on target variables and system balance are examined, confirming that optimising hierarchical structures can effectively enhance system stability. Finally, a non-intervention stabilisation model is constructed, and using an optimised Lotka-Volterra model, it is demonstrated that the system can achieve balance through self-regulation, emphasising the critical importance of rational hierarchical structure configuration in enhancing system resilience. This study provides a theoretical basis for reducing reliance on external interventions and constructing sustainable systems through functional introduction and cycle pattern reconstruction, offering methodological support for system management and regulation in related fields. Future research can further expand the application scenarios of the model, exploring the universality of multi-model systems in different complex systems and dynamic parameter optimisation strategies.

References

[1] Yang Jun, Yang Xiaodong, Lyu Guanghui, et al. Changes in soil respiration rates before and after the conversion of desert forests into farmland and their influencing factors [J]. Soil and Water Conservation Bulletin, 2020, 40 (02): 24-30.

[2] Mao Chao, Yuan Jiayin, Ma Ruiyang. Symbiotic Evolutionary Model of the Construction Robot Industry Ecosystem: Based on the Logistic Model and Lotka-Volterra Model [J]. Research on Science and Technology Management, 2025, 45 (04): 135-146.

[3] Yi Xinran, Lv Tanghong. Hopf bifurcation analysis of a Lotka-Volterra predator-prey system with harvest terms, double time delays, and Allee effects [J]. Journal of Jilin University (Science Edition), 2025, 63 (02): 321-330.

[4] Wang Zhanpeng, Wang Lijin. Neural network learning of parameters of a class of random Lotka-Volterra systems [J]. Journal of the University of Chinese Academy of Sciences (Chinese and English), 2025, 42 (01): 20-25.

[5] Karim A, Aziz W, Amen A. Local Integrability and Linearizability for Three Dimensional Lotka–Volterra Cubic Systems[J]. Qualitative Theory of Dynamical Systems,2024,24(1):30-30.