Environment, Resource and Ecology Journal (2025)
Clausius Scientific Press, Canada
DOI: 10.23977/erej.2025.090109
ISSN 2616-3756 Vol. 9 Num. 1

An Exploration of Ecological Development Based on Simulated Annealing Algorithm and Lotka-Volterra Modeling

Jiaying Zhao[1,†], Jingyan Zhao[1,†], Huanzhou Li[2,†], Jianxin Chen[2], Zeyu Zhang[1,*]

[1]*College of Fisheries, Tianjin Agricultural University, Tianjin, China*
[2]*College of Computer and Information Engineering, Tianjin Agricultural University, Tianjin, China*
[†]*These authors also contributed equally to this work*
**Corresponding author: zzy200410172024@163.com*

Keywords: Simulated Annealing Algorithm; Time Series Model, Lotka-Volterra Model, Simulated Annealing Algorithm, Genetic Algorithm.

Abstract: In this paper, the Lotka-Volterra model, time series model, simulated annealing algorithm and genetic algorithm are used to analyze the agro-ecosystem in multiple dimensions. Firstly, we analyze the ecological evolution of forests after their conversion into farmland and explore the sustainable agricultural management strategies by using time series models to analyze the ecosystem changes. Then, the Lotka-Volterra model was used to construct a food chain model to consider the effects of various factors on the stability of the ecosystem. In addition, the parameters of the Lotka-Volterra model were adjusted to assess the effects of species reintroduction on agroecosystems and analyze the interactions between them. Finally, with the help of simulated annealing algorithms, the effects of organic farming methods on multiple aspects of the ecosystem are explored in different scenarios. In the context of the crucial importance of ecological balance in agricultural development, this study identifies multiple key indicators and constructs a dynamic model based on natural processes and human decision-making, which ultimately comprehensively reveals the dynamic balance mechanism of agroecosystems and provides a scientific basis for agricultural management and ecological protection.

1. Introduction

In this paper, an in-depth analysis of agro-ecosystems is carried out based on simulated annealing algorithm [1] and Lotka-Volterra model [2]. In view of the ecological evolution after the transition from forest to farmland, the time series model is utilized to accurately capture the dynamic changes of the ecosystem [3], and then explore the path of sustainable agricultural management. When constructing the food chain model, the Lotka-Volterra model was used to study the changes in ecosystem stability. In assessing the role of species reintroduction on agro-ecosystems [4], the Lotka-Volterra model parameters were adjusted to analyze their interrelationships with species. As for the study of organic farming methods, simulated annealing algorithms were applied to explore the effects of different scenarios on multiple aspects of the ecosystem [5]. Through the above multi-dimensional research, this paper can comprehensively analyze the agroecosystem, provide scientific and efficient decision-making basis for agricultural management and ecological protection, and promote the development of agroecological field [6].

2. Analysis of the Evolutionary Process

2.1 Transformation of Agro-Ecosystems

The transformation of agro-ecosystems from forest to farmland involves several key factors:

Sharp declines in biodiversity; changes in soil quality; shifts in ecological balance; increased climatic influences; and enhanced human activities.

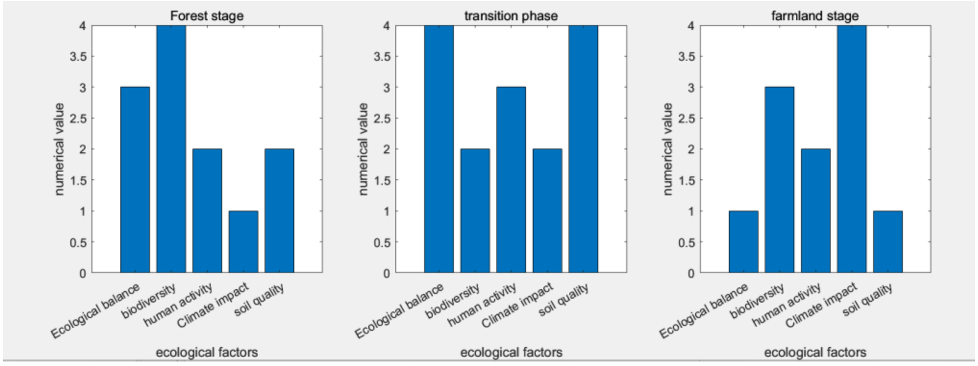

Figure 1. Analysis of conversion factors

(1) Forest stage: In Figure 1, the indicators of the forest stage are almost close to the maximum value, showing a high degree of stability of biodiversity, soil quality and ecological balance, with less influence from climate and fewer human activities.

(2) Transition stage: As the forest is transformed into agricultural land, biodiversity decreases, soil quality slightly declines, and the stability of the ecological balance deteriorates.

(3) Farmland stage: In the farmland stage, biodiversity and soil quality decline significantly, and the ecological balance is affected by human interventions such as pesticides and chemical fertilizers.

2.2 Analysis of Model Construction

Time series models are statistical models that analyze and predict based on time series data. The development of species diversity in ecosystems following the conversion of forests to agricultural land is predicted based on past natural development. These models assume that the data exhibit certain dependencies and patterns over time. In this context, the model predicts the evolution of ecosystems after conversion of forests to farmland in terms of four dimensions: soil quality, species diversity, pest population size, and crop yield.

From the point of view of time series models based on differential equations, their general form can be expressed as:

Let $y_1(t)$, $y_2(t)$,...., $y_n(t)$ be the n variables related to time t. The general form of their rate of change equations is:

$$\frac{dy_1(t)}{dt} = f_1(y_1(t), y_2(t), \ldots, y_n(t), t) \tag{1}$$

$$\frac{dy_2(t)}{dt} = f_2(y_1(t), y_2(t), \ldots, y_n(t), t) \tag{2}$$

$$\frac{dy_n(t)}{dt} = f_n(y_1(t), y_2(t), \dots, y_n(t), t) \tag{3}$$

2.3 Modeling

In this paper, a time series model is employed to simulate the evolution process of the ecosystem. Considering the changes of the farmland ecosystem after deforestation within time t, the following variables are used to describe this system:

$Q(t)$: Soil quality (such as organic matter content).

$S(t)$: Species diversity (such as the number of species).

$P(t)$: Pest population numbers.

$C(t)$: Crop yield.

The relationship between these variables is described by differential equations.

Soil quality $Q(t)$ declines over time, assuming its rate of change is $-\alpha Q(t)$, that is:

$$\frac{dQ(t)}{dt} = -\alpha Q(t) \tag{4}$$

Where in, $\alpha \ge 0$ is the soil quality attenuation coefficient.

Species diversity $S(t)$ decreases over time, assuming its rate of change is $-\beta S(t)$, that is:

$$\frac{dS(t)}{dt} = -\beta S(t) \tag{5}$$

Where in, $\beta \ge 0$ is the species diversity attenuation coefficient.

The population of pests $P(t)$ increases over time, assuming its rate of change is $\gamma P(t)$, that is:

$$\frac{dP(t)}{dt} = \gamma P(t) \tag{6}$$

Where in, $\gamma \ge 0$ is the population growth coefficient for pests.

Crop yield $C(t)$ is affected by soil quality and pest populations, assuming a change rate of $\delta Q(t) - \varepsilon P(t)$, that is:

$$\frac{dC(t)}{dt} = \delta Q(t) - \varepsilon P(t) \tag{7}$$

Where, $\delta \ge 0$ is the positive impact coefficient of soil quality on crop yield, and $\varepsilon \ge 0$ is the negative impact coefficient of pest populations on crop yield.

2.4 Results of Model Realization

The results of the model implementation are shown, with soil quality decreasing over time, reflecting the pattern of change in $Q(t)$.

Species diversity tends to decrease over time, which is consistent with the $S(t)$ hypothesis. Harmful organism populations increased over time, which is consistent with the hypothesis of $P(t)$. Crop yield showed an increasing and then decreasing trend over time as influenced by soil quality and pest populations, which is consistent with the rate of change equation for $C(t)$.

3. Analysis of Changes in Ecosystem Dynamics

3.1 Models of Population Dynamics

Using models like the Logistic growth model or the Lotka-Volterra predator-prey model, establish interaction equations between different species, describing how species change according to the availability of food resources (plants, insects, etc.) and the number of predators. This process can be dynamically adjusted over time.

$$\frac{dp}{dt} = r_p \cdot \mathrm{P} \cdot \left(1 - \frac{P}{K_p}\right) - \alpha_p \cdot \mathrm{P} \cdot \mathrm{I} \tag{8}$$

3.2 Effects of Chemical Substances

Insect population: Can be reflected by adjusting the mortality rate or growth rate of insects to show the impact of pesticides. For example, if the use of a certain pesticide causes an increase in the mortality rate of insects, then the population size of the insects will decrease.

$$\frac{dI}{dt} = r_I \cdot \mathrm{I} \cdot \left(1 - \frac{I}{K_I}\right) + \beta_P \cdot P - \delta_I \cdot I - \gamma_I \cdot C \tag{9}$$

Birds and bats: Similarly, the population growth rates of birds and bats are also affected by the decrease in insects, which may lead to a gradual decline in the number of these species.

$$\frac{dC}{dt} = r_C \cdot C \cdot \left(1 - \frac{C}{K_C}\right) + \eta_I \cdot I - \mu_C \cdot C \tag{10}$$

3.3 Genetic Algorithm Optimization

Genetic algorithms can be used to optimize agricultural decisions (such as the amount of pesticide used, planting density, etc.). Suppose we want to minimize the population of insect species while ensuring that the populations of bats and birds do not fall too low, and the growth of plants remains stable.

1) Objective function: The objective function can be designed to minimize the cost of applying chemicals to the insect population while maximizing the stability of the ecosystem.

$$ObjectiveFunction = \alpha_1 \cdot In\sec tPopulation + \alpha_2 \cdot ChemicalUsage\mathrm{Cos}\,t - \alpha_3 \cdot tabilityIndex \tag{11}$$

Of which, stability indicators can be based on the population stability of all species in the system (for example, measured by variance or other stability metrics).

2) Genetic Operations:

Selection: Choose the best individuals based on their fitness values.

Crossover: Combine features from two parent individuals to generate offspring.

Mutation: Randomly alter certain decision variables (e.g., amount of pesticide used, irrigation levels, etc.)

3) Constraints:

The population size of each species must be above a certain threshold.

The amount of chemicals used in agricultural practices cannot exceed the prescribed safety threshold.

3.4 Particle Swarm Optimization (PSO)

1) The objective function is the same as that of the genetic algorithm, but it finds the global optimal solution through the dynamic adjustment of the particle swarm algorithm.

2) Particle update: The position update formula for particles is:

$$X_i^{k+1} = X_i^k + v_i^{k+1} \tag{12}$$

$$v_i^{k+1} = w \cdot v_i^k + c_1 \cdot r_1 \cdot \left(p_i^k - x_i^k\right) + c_2 \cdot r_2 \cdot \left(g^k - x_i^k\right) \tag{13}$$

4. Species Re-emergence Analysis

4.1 Species Regression Model

One of the most used mathematical models in species reintroduction modeling is the Lotka-Volterra model. By introducing two species (one being an existing agricultural pest population and the other a newly reintroduced predatory insect or other beneficial species), we can study the impact of their dynamic interactions on the agricultural ecosystem.

$N_1(t)$: Population density of existing species (such as pests).

$N_2(t)$: Population density of newly reintroduced species (such as predatory insects).

$P(t)$: Population density of crops.

The return of these two species can be described by the following equation:

$$\frac{dN_1}{dt} = r_1 N_1 \left(1 - \frac{N_1}{K_1}\right) - a_{13} N_1 N_2 \tag{14}$$

$$\frac{dN_2}{dt} = r_2 N_2 \left(1 - \frac{N_2}{K_2}\right) + a_{31} N_1 N_2 \tag{15}$$

Where: r_1 and r_2 are the intrinsic growth rates of species N_1 (pest) and N_2 (predatory insect), respectively. K_1 and K_2 are the environmental carrying capacities for species N_1 and N_2, respectively. a_{13} represents the predatory effect of predatory insects on the pest population. a_{31} represents the impact of pests on the predatory insect population, such as in the food chain.

4.2 Mechanisms of Population Growth in Population Recovery

4.2.1 Population Growth of Newly Introduced Species

(1) Limitations of Environmental Carrying Capacity

The population growth of newly introduced species is initially constrained by the environmental carrying capacity (K). This growth process can be modeled using the Logistic growth model:

$$\frac{dN_3}{dt} = r_3 N_3 \left(1 - \frac{N_3}{K_3}\right) \tag{16}$$

In which: N_3 is the population density of the newly introduced species; r_3 is the intrinsic growth rate of the new species; K_3 is the environmental carrying capacity. In this model, r_3 represents the growth rate of the species in the absence of resource limitations, while K_3 is the maximum carrying capacity of the environment. When the population density approaches or exceeds the environmental carrying capacity, the growth rate gradually slows down and tends towards equilibrium.

(2) Predation impact:

The population growth of newly reintroduced species can also be affected by the predation of existing pest populations. Pests (such as herbivorous insects) may exert predatory pressure on the new species, thereby affecting the population growth of the new species. In the Lotka-Volterra model, the predatory relationship is quantified by the predation rate:

$$\frac{dN_3}{dt} = r_3 N_3 \left(1 - \frac{N_3}{K_3}\right) - c_{3,1} N_1 N_3 \tag{17}$$

The impact of predation on the population of new species depends on the population density and predation rate of the pest. When the pest population density is high, the population growth of the new species will be significantly suppressed.

4.2.2 Growth of Existing Harmful Pest Populations

(1) Limits of Environmental Carrying Capacity

The growth of existing pest populations is also limited by the carrying capacity of the environment. The growth of pest populations is constrained by the availability of food resources; as population density increases, food and habitat resources become scarce, thereby inhibiting their growth. This mechanism can also be described by the Logistic model:

$$\frac{dN_1}{dt} = r_1 N_1 \left(1 - \frac{N_1}{K_1}\right) \tag{18}$$

The regulatory effect of environmental carrying capacity on pest populations manifests as a slowdown in growth rate and a tendency towards equilibrium when pest population density approaches the environmental carrying capacity.

(2) Predation Pressure of New Species

The predatory pressure from newly reintroduced species is one of the important factors affecting the growth of pest populations. In the Lotka Volterra model:

$$\frac{dN_3}{dt} = r_3 N_3 \left(1 - \frac{N_3}{K_3}\right) - c_{3,1} N_1 N_3 \tag{19}$$

As the population of newly reintroduced species gradually increases, the population of pest species comes under pressure from predation, thereby suppressing the growth of pests. Consequently, with the return of the new species population, the population of pests may show a downward trend.

4.3 Description of Data

Given the complex nature of agricultural ecosystems, we must consider both crop growth and pest management in our models. In agricultural ecosystems, crop growth is influenced not only by the interaction between species N_1 and N_2 but also by a variety of factors working together, including seasonal changes and agricultural practices such as the application of pesticides.

Crop Growth: The growth of crop population density $P(t)$ can be represented by the logistic growth model. The crop population density is influenced by its intrinsic growth rate β and the environmental carrying capacity K.

Pest Control: The impact of pest populations on crops can be represented by δ, if pests consume crops.

Pesticide Application: The application of pesticides affects the populations of species N_1 (pests) and N_2 (newly introduced species).

Therefore, the change in crop population $P(t)$ can be described by the following equation:

$$\frac{dP}{dt} = \beta P\left(1 - \frac{P}{K}\right) - \delta P N_1 + \gamma P N_2 \tag{20}$$

4.4 Model Solving

Through the iterative process of genetic algorithms, we can obtain an optimized set of parameters that can bring agricultural ecosystems to an optimal species balance.

For example, through numerical simulation, we may find that when the population of predatory insects is sufficiently large, the number of pests will significantly decrease, and the growth of crops will be improved. As shown in the Figure 2 below.

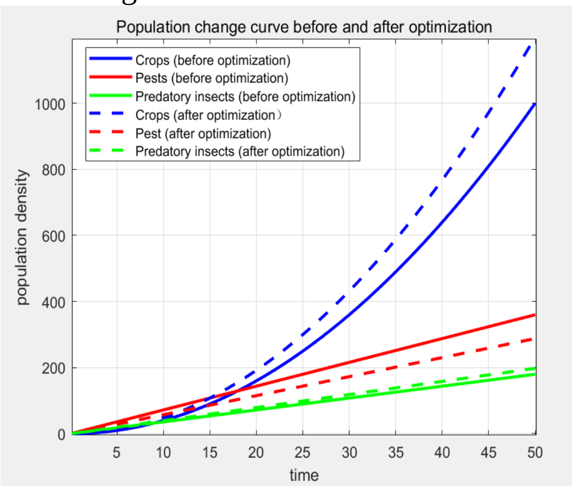

Figure 2. Population changes over time

By comparing the population dynamics before and after optimization, we can draw the following conclusions:

Comparison of population changes: After optimization, the population density of pests has significantly decreased, and at the same time, the growth conditions of crops have shown marked improvement.

Equilibrium of species interactions: After the reintroduction of species, their interactions contribute to effectively reconciling the conflict between pest management and crop growth.

Impact of optimal parameters: A set of optimized parameters has demonstrated the positive interaction formed between predatory insects and pests, ensuring the lasting stability of the agricultural ecosystem.

5. Analysis of Organic Agriculture Applications

As in Figure 3, in terms of pest management, organic agriculture employs biological control and physical methods to manage pests, which have slower effects and require optimization. Regarding crop health, organic agriculture focuses on soil quality and ecological balance, reducing the use of chemical fertilizers and enhancing crop health with organic fertilizers and crop rotation. Resistance and growth rate are the standards for measurement. In terms of propagation methods, organic agriculture utilizes natural pollination and relies on insects and other organisms, with crop reproduction being influenced by the health of the crops themselves and the activities of the biological community. Biodiversity is enhanced through organic agriculture, which improves ecosystem health and contributes to pest control and ecological balance, providing ecosystem services. In terms of cost and benefits, organic agriculture has high initial investment, but in the long run, ecological improvements and increased production efficiency may bring economic benefits.

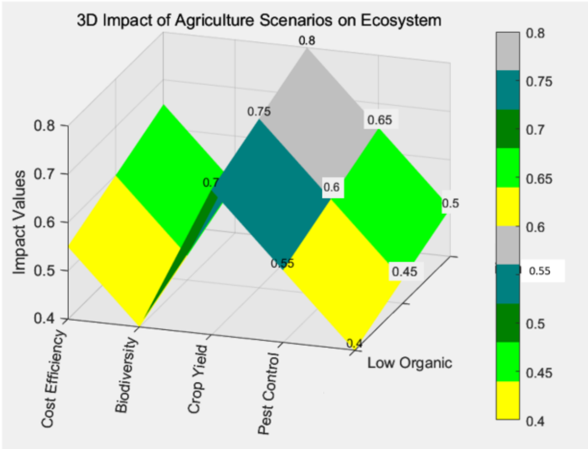

Figure 3. Three- dimensional impacts of agricultural scenarios on ecosystems

5.1 Modeling

(1) Crop and Pest Modeling

The Lotka-Volterra model simulates the interaction between crops and pests. The model correlates fluctuations in pest populations with changes in crop populations.

(2) Modeling Healthy Plant Reproduction

Organic agriculture enhances soil quality and promotes healthy crop growth. Growth models depict plant health and reproduction.

(3) Biodiversity Modeling

Organic agriculture enhances ecological stability by increasing biodiversity. Model simulations of species population changes evaluate the impact of diversity on ecological balance.

5.2 Application of Intelligent Optimization Algorithms

To find the best agricultural management strategies, we can employ the Simulated Annealing (SA) algorithm to optimize the key parameters in the model. Simulated Annealing is an algorithm capable of efficiently finding the global optimum solution and is suitable for solving complex problems that include multiple local optimum solutions.

5.2.1 Initialization Phase

(1) Define the objective function

Our objective function is the weighted sum of multiple ecological indicators, including:

Crop health: Represents the growth status of crops, which may be related to the growth rate and stress resistance of crops.

Pest population: Represents the number of pests, reflecting the threat of pests to crops.

Biodiversity: Represents the diversity of species in the ecosystem.

The objective function (f) can be expressed as the weighted sum of these indicators:

$$f(x) = w_1 H_{crop} + w_2 I_{pests} + w_3 B_{biodiversity} \quad (21)$$

(2) Initialize temperature and status

Initial solution: Randomly select an initial solution $\theta_0 = (\theta_1, \theta_2, \ldots, \theta_n)$, where θ_i, is the parameter to be optimized, which may include biological control coefficients m, crop growth rate r_p, and growth rate of biodiversity species r_B, etc.

Initial temperature: Set the initial temperature T_0, the higher the initial temperature, the wider the range of exploration for the system. The choice of this temperature can affect the convergence speed of the algorithm and the finding of the global optimal solution.

(3) Define neighborhood operations: Neighborhood operations determine how to generate neighborhood solutions from the current solution. In this context, new solutions can be generated by tweaking parameters. For example, by increasing or decreasing the biological control coefficient m, adjusting parameters for crop growth r_p, etc., neighborhood solutions are generated θ_{new}.

5.2.2 Simulated Annealing Process

(1) Calculate the objective function value: Calculate the objective function value $\theta_{current}$ corresponding to the current solution $f(\theta_{current})$.

(2) Criteria for accepting new solutions: Use the Metropolis criterion to decide whether to accept the new solution.

The specific criteria are:

1) If the objective function value of the new solution is less than that of the current solution, then accept the new solution.

2) If the objective function value of the new solution is greater than that of the current solution, the probability of accepting the new solution is:

$$P(\theta_{new}) = \exp\left(\frac{f(\theta_{current}) - f(\theta_{new})}{T}\right) \tag{22}$$

In which, T is the current temperature and is the probability of accepting a new solution. This formula implies that when the objective function value worsens, it is more likely to accept a worse solution at higher temperatures. As the temperature decreases, the probability of accepting a worse solution decrease, approaching a local optimum.

(3)Temperature drop:

After each iteration is completed, the temperature T decreases, usually according to the following rule: the temperature is reduced.

(4) Termination Criteria:

The termination of an algorithm can be based on two conditions:

1) Reaching a preset maximum number of iterations.

2) The temperature T drops to a small value, meaning the algorithm has converged.

5.3 Analysis of Results

Figure 4 shows the comparison between green and conventional agriculture.

(1) Crop and Pest Management: Simulations indicate that biological control measures in organic agriculture enhance crop health and reduce pest populations. Adjusting biological control parameters m effectively suppresses pests, ensuring stable crop growth.

(2) Plant Health and Reproduction: Organic agriculture improves crop health and reproductive capacity. Improved soil quality and reduced use of chemical fertilizers enhance crop growth rates, while increased natural pollination promotes reproductive success.

(3) Biodiversity: Simulations show that organic agriculture increases ecosystem biodiversity, which aids in pest management, enhances soil fertility, and provides more ecosystem services.

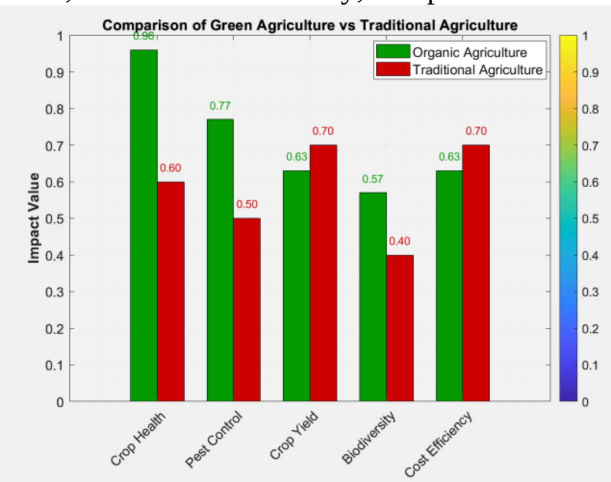

Figure 4. Comparison of Green Agriculture and Traditional Agriculture

6. Conclusions

This study integrates simulated annealing algorithm, Lotka-Volterra model and other related algorithms and models to systematically analyze agroecosystems. The time series model was used to accurately capture the dynamic trajectory of the ecosystem during the transition from forest to farmland, which provides an indispensable basis for exploring sustainable agricultural management models. The food chain model based on the Lotka-Volterra model enables a quantitative assessment of the ecological stability of herbicides and pesticides, which provides key data to support the rational use of agrochemicals. When evaluating the ecological effects of species reintroduction and organic farming methods, the simulated annealing algorithm reveals the laws behind the complex ecological responses by virtue of its efficient searching ability. The innovative combination of these algorithmic models successfully analyzes the complex interconnections of agroecosystems. The results are directly applicable to agricultural practices, providing agricultural managers with practical decision-making solutions to balance ecological protection and production efficiency.

References

[1] Dong Lingbo. Simulation of forest multi-objective management planning based on simulated annealing algorithm [D]. Northeast Forestry University, 2016.DOI:10. 27009/d.cnki. gdblu.2016. 000042.

[2] Zhang Haonan. Research method of service ecosystem evolution based on Lotka-Volterra model[D]. Hangzhou University of Electronic Science and Technology, 2024.DOI:10. 27075/d.cnki. ghzdc.2024.001295.

[3] Shao Jia. Research on filling missing values of time series in ecological stations [D]. Beijing Forestry University, 2017. DOI: 10.26949/d.cnki.gblyu.2017.000365.

[4] Deng R , Kang B , Zhang L ,et al.Weighted mapping of productivity potential based on simulated annealing algorithm for well placement optimization[J].Journal of Petroleum Exploration and Production Technology, 2024, 14(11):3031-3043.DOI:10.1007/s13202-024-01863-y.

[5] Deng Qiyue, Song Kebin. Thinking about the integration and development of ecological agriculture and organic vegetable production[J]. Southern Agricultural Machinery,2024,55(23):74-77.

[6] Zheng Yan. Outstanding problems in China's agro-ecological environment and the thinking of future scientific and technological innovation[J]. Science and Innovation,2023,(05):158-160.DOI:10.15913/j.cnki.kjycx.2023.05.051.