Prediction and Conservation Recommendations for the Effects of Diversified Drought on Plant Community Species

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Abstract. Based on the analysis of plant community data and climate data, this paper established a plant community competition prediction model that includes weather and environmental factors by utilizing species competition theory and the Lotka-Volterra model. During the model construction process, the actual data was pre-processed and summarized for analysis, which ultimately determined the parameters of species quantity, growth rate, and precipitation, improving the accuracy and reliability of the model. Meanwhile, using the Lotka-Volterra model, a relationship model between biomass and time was established, and through the simulated annealing algorithm, two optimal species quantity changes were obtained. Finally, this paper optimized the multi-factor plant community Lotka-Volterra model through the genetic algorithm and obtained the optimal solution: the plant community can achieve the most beneficial competitive state with four species. This further proves the rationality and robustness of the model and also provides new methods and ideas for the management and protection of ecosystems. In summary, the results of this paper are of great significance for the stability and sustainable development of ecosystems and provide useful references for solving the problem of plant community competition and ecosystem stability.

Keywords: Prediction model for plant community competition, Lotka-Volterra model, Changes in species abundance, Genetic annealing algorithm.

1. Introduction

1.1. Background

For a long time, drought has been one of the greatest challenges faced by mankind. Though advancements in technology have alleviated some of the impacts of drought, it still brings disastrous consequences. With rapid economic development, the problem of water scarcity has become increasingly severe, leading to the expansion of arid and semi-arid areas and exacerbating drought conditions, which has become an urgent global issue in our society today.

Plants are among the most vulnerable organisms to the impacts of drought because different plant species exhibit varying responses to drought stress. Multiple studies have shown a correlation between species abundance in plant communities and their drought adaptability, which significantly affects the long-term survival of plant communities.[1] Therefore, exploring the drought adaptability of different plant species is crucial for mitigating the current drought situation and provides valuable information for related studies.

1.2. Objectives

In order to explore the temporal dynamics of different plant communities under various irregular weather cycles, including periods of drought despite sufficient precipitation, and to consider the interactions between different species, this study aims to establish a plant species competition prediction model that incorporates the effects of weather and environmental factors [2]. This model predicts how the plant community will evolve over time under various irregular weather cycles and elucidates the relationship between drought adaptability and plant community abundance. The model analyzes and summarizes changes in species and plant community abundance under different environmental conditions. Finally, measures are proposed to ensure the long-term survival of plant communities and their impacts on the larger environment are explained.The main goals of this article include:

Develop a multi-factor Lotka-Volterra model for plant communities based on historical data of grassland plant growth rates.

Further optimize the model by combining grassland biomass and analyzing the optimal solution for species abundance using genetic algorithms.

Summarize the measures to ensure the long-term survival of plant communities by integrating the optimized model and the discoveries obtained during the problem-solving process.

In summary, this article develops an interdisciplinary approach to develop a plant species competition prediction model that considers the impact of weather and environmental factors. The model provides a comprehensive understanding of how plant communities respond to irregular weather cycles and reveals the relationship between drought adaptability and species abundance. These findings are of great significance for formulating strategies for the long-term survival of plant communities and mitigating current drought [3]. Figure 1 shows the technical roadmap of this paper.

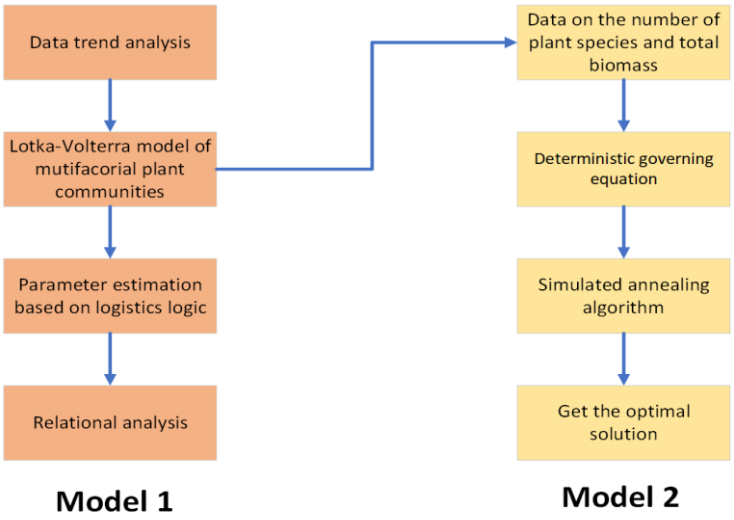


Figure 1. Technology roadmap

2. Research Methodology

According to the research objectives, the following hypotheses were proposed:

Hypothesis 1: It is hypothesized that when two populations compete with each other, the growth rate of one population will decrease because the negative impact on both species is greater than the positive impact, which simplifies the omission of the latter in the analysis process.

Hypothesis 2: It is hypothesized that the sample area only includes two types of plants and one herbivorous animal, which eliminates the potential impact of other species and is conducive to the establishment of the model [4].

Hypothesis 3: It is hypothesized that the scope and frequency of drought are limited to the two extreme conditions of high and low to simplify the prediction process, improve the credibility of results, and enhance computational efficiency.

Hypothesis 4: It is assumed that the research data is accurate because it is assumed that there is no significant deviation in the data on grassland biomass, species growth rates under favorable conditions, and pollution gradient indices in the study area. Such assumptions are favorable for model development.

3. Model building

3.1. Data description

Given the large number of species information and complexity of grassland environmental information, a random sampling method was adopted in this study to obtain representative samples.

By randomly selecting three different longitude and latitude positions, namely the Hulunbuir grassland, the Pampas grassland, and the African savannah, the centers of which were used as the center of a circle with a radius of approximately 30 kilometers, the samples were taken within this area. This sampling method has the advantages of randomness, representativeness, and repeatability, which can effectively avoid sampling bias and improve the representativeness and credibility of the samples (Figure 2).

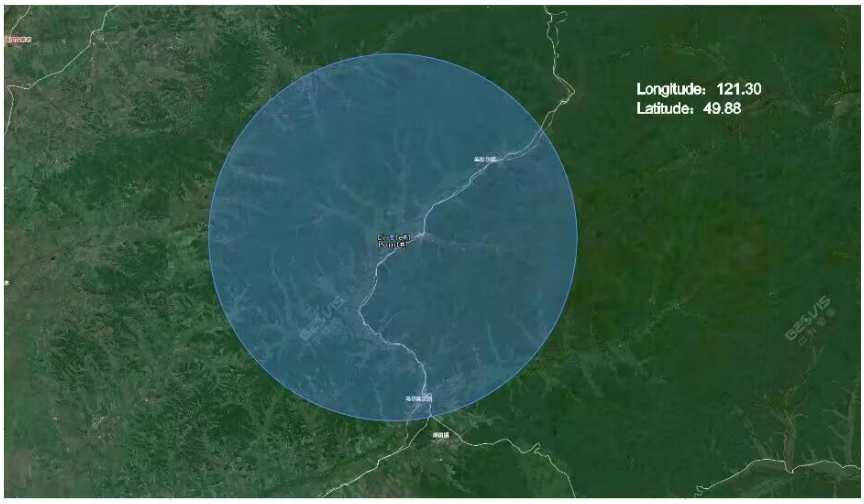


Figure 2. Sampling example diagram

According to the distribution information of related plants, the percentage of plant species in the total grassland biomass in each of the three regions is summarized in Table 1.

Table 1. Percentage of plant species in the total grassland biomass in each of the three regions.

Region	Percentage of total plant biomass in the total biomass.
Hulunbuir grassland	0.667%
Pampas grassland	0.583%
African savannah	0.51%

The average percentage of grassland species in the total biomass in the three randomly selected geographical locations is 0.583%. In addition, this article further investigated the number of plant species in each of the Hulunbuir grassland, Pampas grassland, and African savannah, as shown in Table 2.

Table 2. Number of plant species in each of the three regions.

Region	Number of species
Hulunbuir grassland	1504
Pampas grassland	1243
African savannah	825

3.2. Lotka model without environmental considerations

In order to better represent the changes of plant communities in various irregular weather cycles over time, it is necessary to prioritize the discussion of the impact of grassland weather conditions on the growth rate of plant communities and the inter-species interaction between communities. In biology, the growth rate of plant communities generally follows the fitting method of the logistic curve. Positive and negative interactions are the main types of inter-species interaction between plant communities in grasslands [5].

As an example, this study used data from 2010 to 2020 in Hulunbuir grassland to group ten common plant communities under the same environmental conditions based on their distance properties, roughly divided into long-distance and short-distance groups. The relationship between grassland plant community spacing and community coverage is shown in Table 3.

Table 3. Relationship between inter-species interaction and rate of three common plants in Hulunbuir grassland.

Comparison	L	S	*p*	R^2
Long-distance group	20	0.9	-0.77	0.79
Short-distance group	6	0.63	-0.42	0.81

Wherein, L represents the spacing between plant communities, S represents the coverage of plant communities, *p* represents the Pearson correlation coefficient, and R^2 represents the degree of linear fitting.

From the perspective of space and time, the coverage of plant populations and the distance between communities in grassland ecology show a significant negative correlation, which means that under the same environmental factors, grassland plant communities are basically in negative interaction, that is, there exists inter-species competition. Therefore, this study established a Lotka-Volterra model that includes mutual competition between populations.

Assuming that the evolution of the number of two populations follows the logistic law when they live independently in the natural environment. When they compete with each other, this competition will slow down the growth rate of the other population. Specifically, the degree of slowing down the growth rate is proportional to the product of the number of the two populations.

Therefore, the species competition model without environmental factors is considered first, and the established differential equation model is:

$$\begin{cases} \frac{dx_1}{dt} = r_1 x_1 \left(1 - \frac{x_1}{N_1} - \alpha \frac{x_2}{N_2}\right) \\ \frac{dx_2}{dt} = r_2 x_2 \left(1 - \frac{x_2}{N_2} - \beta \frac{x_1}{N_1}\right) \end{cases} \tag{1}$$

where r is the growth rate, N is the maximum capacity of the species, α is the competition coefficient of species 2 to species 1, and β is the competition coefficient of species 1 to species 2[6].

Based on the relevant data on the growth rate of grassland plant communities in Hulunbuir grassland, Pampas grassland, and African savannah, the parameters of model for species X_1 and X_2 are assumed to be:

$$\begin{cases} r_1 = 0.1, \frac{1}{N_1} = 0.001, a_1 = 0.0001 \\ r_2 = 0.2, \frac{1}{N_2} = 0.002, a_2 = 0.0002 \\ x_1(0) = 100, x_2(0) = 200 \end{cases} \tag{2}$$

According to the model parameters, it can be inferred that species X_1 has a relatively low growth rate, but there is less competition within the species, and it is not easily influenced by species X_2. Therefore, from a long-term competition perspective, the number of X_1 species in the grassland ecosystem shows a positive correlation trend with time, indicating that X_1 species has an advantage in this ecological system.

In contrast, species X_2 has a faster growth rate, relatively high growth rate, but there is more competition within the species, and is easily influenced by species X_1. Therefore, in long-term competition, the number of X_2 species shows a negative correlation trend with time. The numerical results below also support this speculation, as shown in Figure 3.

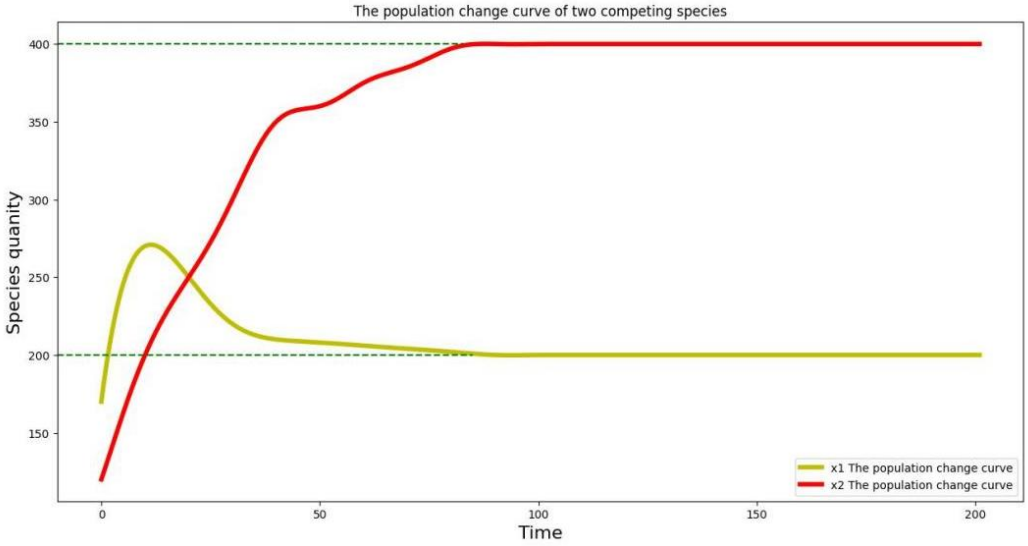


Figure 3. Graph depicting the relationship between species quantity and time

The numerical simulation results show that the quantity of species X_1 grows rapidly at first, reaches its maximum and then slowly declines, ultimately stabilizing at a quantity of approximately 200. In comparison, the growth rate of species X_2 is much slower, but it maintains a relatively stable growth until it reaches an equilibrium point with a quantity of approximately 400.

Based on the above competition model that only considers the interaction between species, an environmental factor, such as precipitation, can be further included. Moreover, the model can be expanded to consider more species to further explore the relationship between precipitation and the number of plant populations in the grassland ecosystem, and to construct a Lotka-Volterra model that includes environmental factors.

Expanding formula (2), we can obtain:

$$\left\{\frac{dx_i}{dt} = r_i x_i\left(1 - \frac{x_i}{N_i} - \sum \alpha_k^i \frac{x_k}{N_k}\right)\right. \tag{3}$$

Here, r_i denotes the growth rate, N_i denotes the maximum capacity of the species, and α^i_k denotes the competition coefficient of species k on species i[7].

In this model, the indicator for evaluating the relationship between precipitation and species population is the growth rate of the species. Let's assume there are two relationships to be analyzed: Suppose there is a linear positive correlation between precipitation and population growth rate. If we take precipitation (h) as the independent variable, the basic relationship between the growth rate (r_i) and precipitation (h) can be expressed as:

$$r_i(t) = k * h(t) \tag{4}$$

That is, within a certain time frame, an increase in precipitation will lead to an increase in the growth rate of grassland plant populations. However, it is necessary to consider the following situations regarding precipitation in the environment:

Abnormal weather phenomena, such as a sudden increase in precipitation during a drought period.

A sustained increase in precipitation may cause soil compaction, which can lead to oxygen deficiency in grassland plants and reduce the growth rate of plant communities, resulting in a decrease in the number of species.

Therefore, we can conclude that when precipitation changes, the growth rate of grassland plant populations will also change accordingly. Assuming that the initial quantity of the species is less than the maximum carrying capacity of the environment, the number of plant populations will increase. However, as precipitation continues to increase, the growth rate will become saturated, the rate of increase will slow down, and it will eventually stop growing after reaching maturity.

The logistic model can be used to address such a problem, and the basic formula is as follows:

$$f(x) = \frac{L}{1 + e^{-k(x - x_i)}} \tag{5}$$

Assuming that the growth rate is also 0 when precipitation is 0, we can improve the logistic function by subtracting the value when precipitation is 0. This will satisfy the condition where the growth rate is 0 when precipitation is 0. One way to do this is to construct a modified logistic function.

$$r_i(t) = \frac{L_i}{1 + e^{-k_i * h(t)}} - \frac{L_i}{2} \tag{6}$$

Here, Li refers to the maximum growth rate of species i, ki refers to the steepness of the logistic growth curve, and h(t) refers to the precipitation at time t. We can substitute the above equation into equation (4) and rewrite them as functions of time t[8]:

$$\begin{cases} \frac{dx_i(t)}{dt} = \left(\frac{L_i}{1 + e^{-k_i * h(t)}} - \frac{L_i}{2}\right) x_i(t) \left(1 - \frac{x_i(t)}{N_i} - \sum_{k \neq i} \alpha_k^i \frac{x_k(t)}{N_k}\right) \end{cases} \tag{7}$$

Thus, we can derive the growth rate as a function of precipitation, as shown in Figure 4.

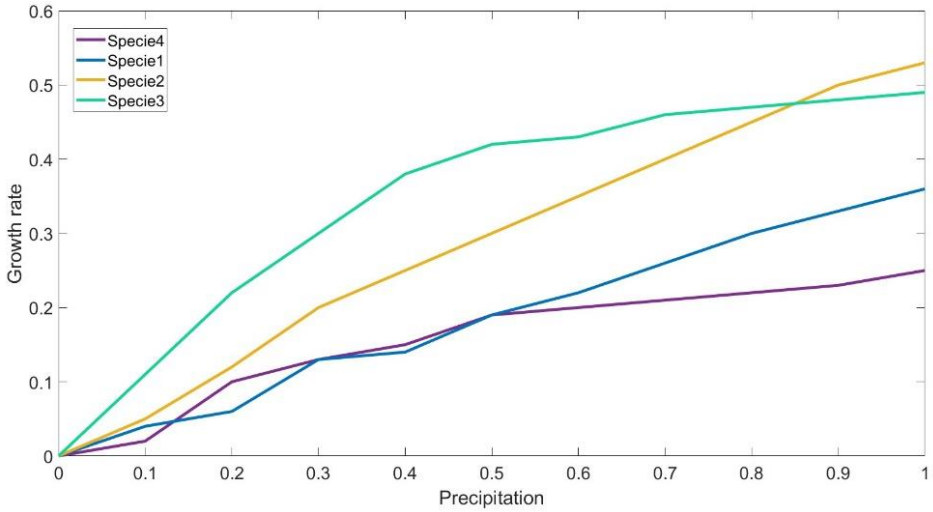


Figure 4. Graph depicting the relationship between species growth rate and precipitation.

The graph above describes the effect of precipitation on the growth rate curve under multiple parameter settings, with precipitation normalized to a range of 0-1. The above differential problem can be solved by applying an improved Euler method.

3.3. The Lotaka-Volterra model of biomass vs. time

Let's define the quantity M as the number of species in a certain region of the grassland, which can roughly estimate the species M in a certain area of the grassland as $M \leq 10$. Let U represent the biomass and X(t) represent the population quantity of a certain species that changes over time.

$$U = M * x(t) \tag{8}$$

To promote community diversity, it is necessary to maximize the total biomass of the grassland by ensuring that the quantity of each plant species reaches its maximum value. To achieve this, a comprehensive Lotka model that considers environmental factors can be established, and a comprehensive optimization algorithm can be used to solve the optimal solution.

In the solution process, it is necessary to consider the random factor of precipitation and accept a solution that is worse than the current solution with a certain probability, to avoid getting trapped in a local optimum. The quantity of species can be taken as the independent variable, the total biomass as the dependent variable, and the quantity of species as the constraint. The data can be substituted into

the differential equation for the population quantity as a function of time, and the Euler method can be used to solve the differential equation.

Due to the strong nonlinearity of such problems, it is recommended to use a simulated annealing algorithm for solution [9,10]. The pseudocode is shown in Table 4.

Table 4. Pseudocode for Simulated Annealing Algorithm

Algorithm:
Inputs: M, r_i, h(t), $X_i(t)$
Output: U_i
1. For i = 1 to the number of iterations:
2. Solve the differential equation system using the Euler method to obtain the curves of the plants quantity changes over time.
3. Check if the inputs meet the constraint conditions. If they do, set the fitness to the value of the actual objective function. Otherwise, use the Lagrangian method to add the fitness to a larger value.
4. Iterate using a genetic algorithm until the fitness curve converges to the optimum solution.
5. Return the value of the optimal fitness.
end

The graph depicting the relationship between the number of species and the total biomass can be obtained through the algorithm described above, as shown in Figure 5.

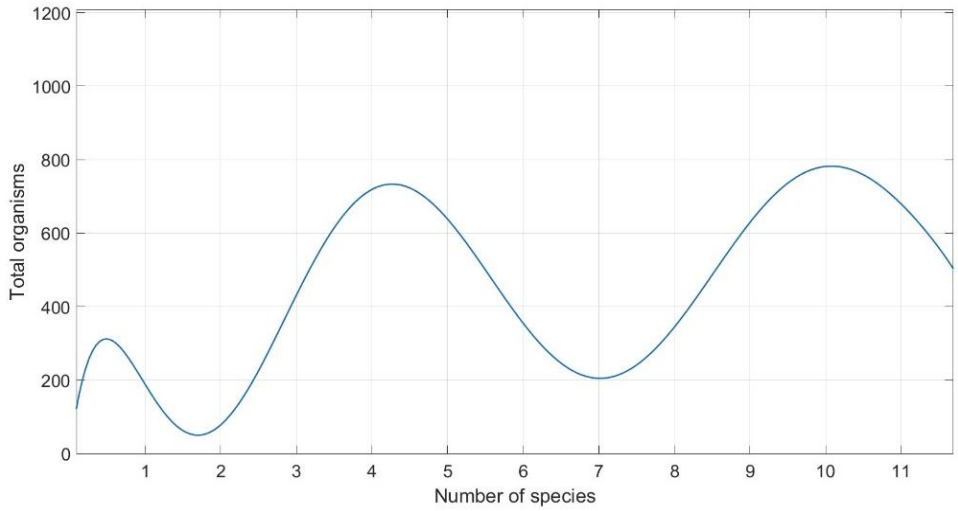


Figure 5. Graph showing the relationship between the number of species and the total biomass

By changing the growth rate ri and rainfall h(t), and using the simulated annealing algorithm to solve the Lotka model twice, it was determined that when the number of species was 3.98 and 9.79, the total biomass was highest, and the plants could benefit the most. Meanwhile, as the number of species gradually increased, the total biomass of the species showed a slow upward trend, but two higher peaks also appeared. This suggests that an increase in the number of species can improve the stability and survival of the plant population, but the relationship between species growth and species quantity is not very close, and there is still an optimal condition.

Through further analysis of the above conclusions and relevant data, this study found that in order for species to benefit, it is not only necessary to have a high total biomass, but also to have an increasing number of surviving plant populations that can trend towards relative stability in the long-term ecological environment.

4. Results

4.1. Result 1

After using the improved Euler method for numerical solution of differential equations, the following results can be obtained: During a normal weather cycle, the population of a plant community continues to grow. However, when faced with an irregular weather cycle, the population may experience a sudden downward trend. In addition, as the number of species increases, the population may gradually decrease over time, but the magnitude of the decrease is much smaller than the impact of the weather environment on the community. Therefore, it can be inferred that the relationship between species and the irregular weather cycle are negatively correlated with the population of the plant community, but the impact of irregular weather cycles is much greater than the interaction between species, as shown in the Figure 6.

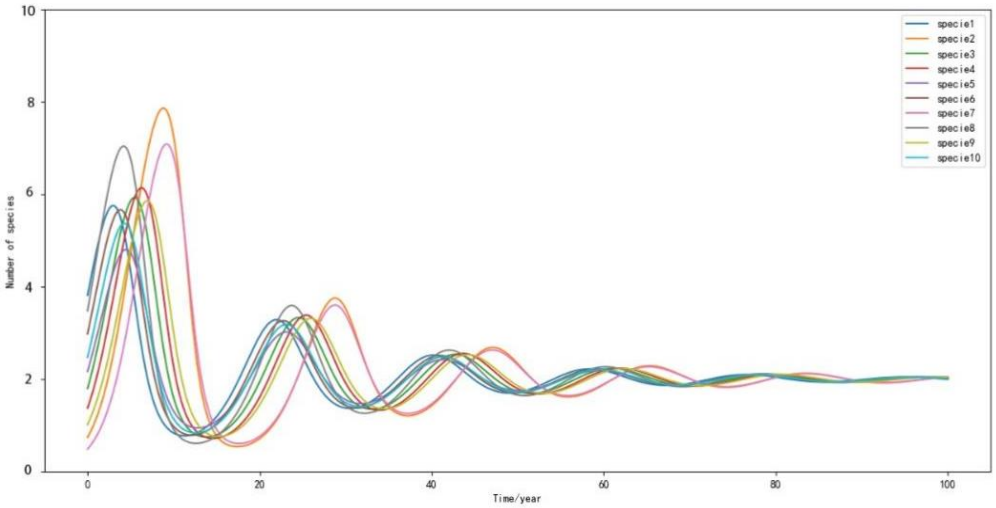


Figure 6. Graph showing the relationship between population and irregular weather cycles

4.2. Result 2

The optimization model for plant species based on logistics logic, and the prediction model of plant species under different environmental factors, can help predict changes in plant species under different environmental conditions. In addition, using the data on the number of plant populations and vegetation coverage on the Hulunbuir grassland from 2010 to 2020, we can analyze the growth trend of plant communities and obtain results, as shown in Figure 7.

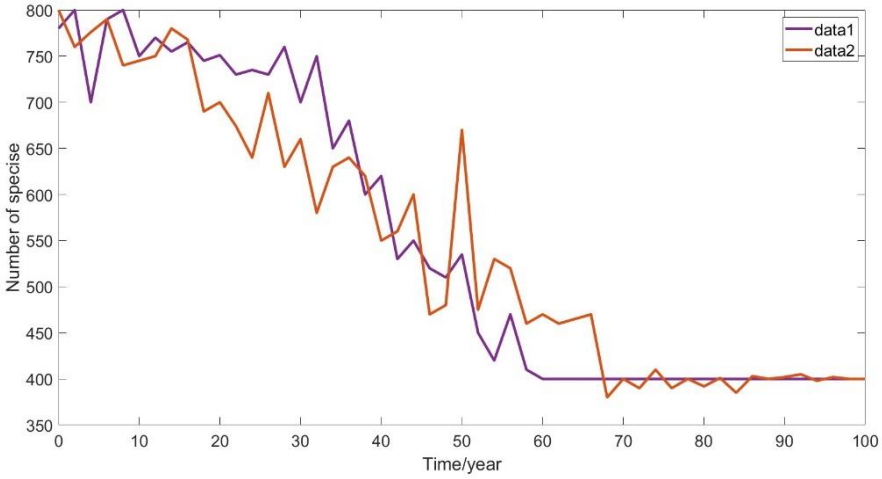


Figure 7. Trend chart of changes in the number of plant populations

Both populations slowly increase over time, but four of them tend to gradually stabilize, which indicates that plant communities can gradually form a balanced state, while the other ten populations continue to grow over time, indicating that the growth of plant communities is still in an unstable state. In conclusion, it can be inferred that when the number of species is four, the total biomass of the community is relatively large, and the growth of the population can gradually trend towards a relatively stable state in the long-term ecological environment, thus achieving the most favorable situation.

5. Analysis of experimental results

5.1. Sensitivity analysis

In the model, α^i_k is the competition coefficient of species k to species i, and X_0 is the initial capacity of n species. These two hyperparameters are factors that affect the results. Therefore, this study conducted sensitivity analysis to explore the degree of influence of these two hyperparameters on the model. Specifically, multiple simulation experiments were conducted by 3% changes in the standard values of these two hyperparameters. Finally, by calculating the mean and error of the objective function, the degree of influence of these two hyperparameters on the results was obtained. This analysis has important academic and practical value for a deeper understanding of the dynamic evolution mechanism of ecosystems and improving their predictive ability. The results are shown in Figures 8 and 9.

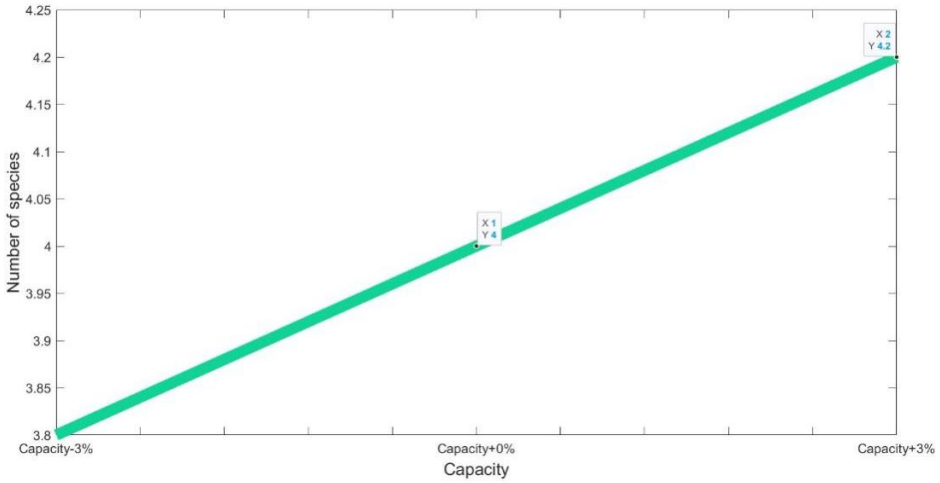


Figure 8. Influence of the initial capacity of n species on the results

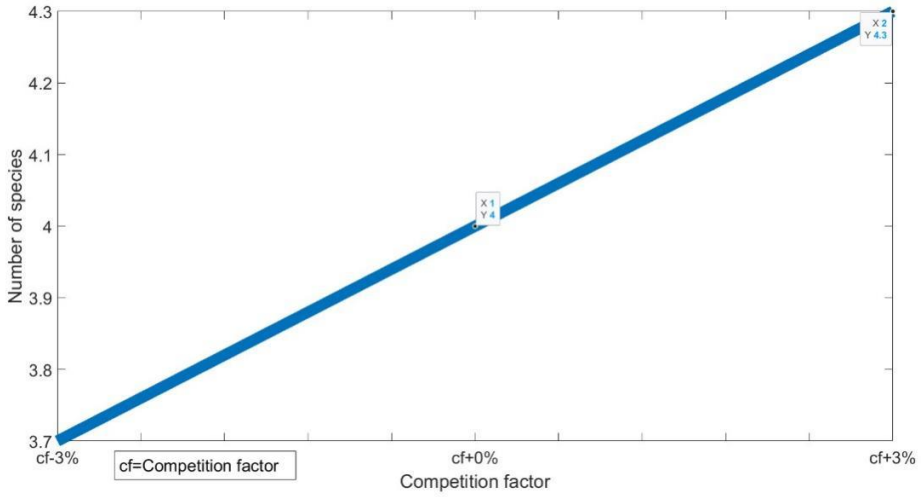


Figure 9. Influence of competition coefficients on the results

This study conducted sensitivity tests on the competition coefficients α^{i}_{k} and initial capacity X_0 of species, and optimized the multi-factor plant community Lotka-Volterra model using a genetic algorithm. By comparing the optimized model results with real situations, it was found that the deviation of the optimal solution is between 0.2~0.3, indicating that the predictive accuracy of the model is basically in line with the actual situation. These results not only demonstrate the rationality and robustness of the model, but also further verify the effectiveness of the method. The application of this multi-factor optimization model has important academic and practical significance for a deeper understanding of the dynamic evolution mechanism of plant communities, improving their predictive ability, and enhancing the ability to protect and manage ecosystems.

5.2. Strengths

Based on scientific and reasonable logic, reliable and clear theoretical descriptions, including the established model and conclusions, were obtained after testing the relevant data of grasslands.

Sensitivity analysis was conducted on the model to verify the effectiveness of the model under parameter changes, and further prove the robustness of the model.

By optimizing the relevant biological research data, the computational efficiency of the model was further improved. In addition, to better fit the actual situation, the factors of species competition and balance in the ecological environment were added to the model, making the model more consistent with the actual situation.

6. Conclusions

This paper mainly studied the competition problem of plant communities under different weather conditions and established a plant community competition prediction model that included weather environmental factors. Through the analysis and summary of actual data, combined with species competition theory and Lotka-Volterra model, the dynamic changes and changes of species quantity of plant communities were explored. The study showed that when the number of species is 4, the plant community can achieve the most beneficial competitive state. This paper also optimized the multi-factor plant community Lotka-Volterra model using a genetic algorithm to improve the accuracy and reliability of the model. This paper has important implications for the stability and sustainable development of ecosystems. In the future, this model can be further applied in the fields of plant ecology, ecosystem management, and environmental protection to better solve ecological problems in the real world.

References

[1] Science - Plant Science; Researchers from Western Sydney University Report Recent Findings in Plant Science (A Simple Method for Simulating Drought Effects on Plants)[J]. Science Letter,2020.

[2] Gallego Irene,Narwani Anita. Ecology and evolution of competitive trait variation in natural phytoplank ton communities under selection.[J]. Ecology letters,2022,25(11).

[3] Kang Haibin,Chang Mingjie,Liu Shutong,Chao Zhi,Zhang Xinping,Wang Dexiang. Rodent-mediated plant community competition: what happens to the seeds after entering the adjacent stands?[J]. Forest Ecosystems,2020,7(1).

[4] Ecology Research; Findings from Nicolaus Copernicus University Has Provided New Data on Ecology Research (Functional traits and environmental characteristics drive the degree of competitive intransitivi ty in European saltmarsh plant communities)[J]. Ecology Environment & Conservation,2018..

[5] Climate Change; Researchers from University of Manchester Discuss Findings in Climate Change (Leg acy effects of drought on plant-soil feedbacks and plant-plant interactions)[J]. Global Warming Focus,2017.

[6] Bourquin Antoine. Persistence in Randomly Switched Lotka-Volterra Food Chains[J]. ESAIM: Probability and Statistics,2023,27.

[7] Pah C. H.,Rosli A.. On a Class of Non-Ergodic Lotka–Volterra Operator[J]. Lobachevskii Journal of Mathematics,2022,43(9).

[8] Li Shanbing,Wu Jianhua. The effects of diffusion on the dynamics of a Lotka-Volterra predator-prey model with a protection zone[J]. Calculus of Variations and Partial Differential Equations,2022,61(6).

[9] Jin Hongbin,Luo Weilin,Li Hao,Dai Lingyan. Underdetermined blind source separation of radar signals based on genetic annealing algorithm[J]. The Journal of Engineering,2021,2022(3).

[10] Wu Xiaoli,Wu Dang,Ma Xiufeng. Analysis of the Implementation Effect of College Curriculum Ideological and Political under the Background of Ecological Sustainable Development[J]. Journal of Environmental and Public Health,2022,2022.