

Drought adaptation of plants based on improved Lotka-Volterra model

Zonghao Lin^{1, #}, Hao Zhang^{2, *, #}, Ye Liu^{2, #}

¹Zhuoyue Honors College, Hangzhou Dianzi University, Hangzhou, Zhejiang, 310018

²Automation, Hangzhou Dianzi University, Hangzhou, Zhejiang, 310018

*Corresponding author: zhanghao@hdu.edu.cn

#These authors contributed equally.

Abstract. In arid environments, plant communities often cooperate to fight the harsh conditions. In order to study the interaction between plant populations and explore their survival under drought conditions, an improved Lotka-Volterra model was established by means of mechanism analysis to consider the interaction between different plant species, and the species correlation degree was added. Light, water, air competition among plants and other important parameters affecting plant growth, a relatively complete model of plant drought adaptability was fitted. Then, the fourth order Runge Kutta method was used to solve the model numerically, and the relationship between the amount of various plants in the community with time was obtained, and the relationship between plant populations under drought conditions was explored.

Keywords: Arid environments, plant interactions, Lotka-Volterra model

1. Background introduction

Plants are an important part of life on Earth, absorbing sunlight, water, and carbon dioxide through photosynthesis and converting them into life energy. However, plants also face a variety of pressures, including climate change and natural disasters such as drought, along with increased precipitation variability due to anthropogenic climate change[1]. Forests in many parts of the world are experiencing increased tree mortality and widespread forest die-offs[2]. Drought is one of the most important abiotic stresses and hurts plant growth around the world. Drought is a natural phenomenon caused by an insufficient supply of fresh water. It can last for months or years[3]. Drought is not confined to a specific area or period in nature, it occurs repeatedly and is difficult to predict[4]. Drought events are predicted to become more widespread, widespread, and extreme in the future as the global climate changes[5]. Therefore, improving the rapid detection method of drought stress has become an important research field.

Some researchers have revealed the adaptability of different plant species to drought by studying their morphological and physiological characteristics. Studies such as Qianwen G[6].show that plant species composition and life forms vary greatly in arid areas during the succession stage, and key factors affecting community composition and species diversity have been ide. LI Rui et al.[7]. analyzed the species diversity of ecotone in the ecosystem and found that there were obvious differences among vegetation zones, among which the ecotone had the highest richness index and comprehensive degree. The study of Song W et al.[8] showed that large tree species had a strong ability to cope with drought stress, and their stem water content could reach a low level and maintain for a long time under drought stress, while small plants were more likely to die due to drought stress due to their thin stems. Peng L et al.[9]. studied plant species interactions and found that the presence of a third plant species can regulate plant interactions, demonstrating the importance of species coexistence and biodiversity maintenance. It can be seen that different plant community species have a great impact on plant drought adaptability, and the research on this aspect is of great significance for plant planting in a drought environment. As can be seen from the above literature, there are few studies on the effects of interaction between different plant species on plant survival in drought environment, which can be further discussed and studied.

However, the relationship between plant population type and drought adaptability is complex and influenced by many factors. With further study on the drought adaptability of plants, people gradually realize that different plant populations have different drought adaptability. Future studies need to further explore the formation mechanism of drought adaptation in plants and the changing rules of drought adaptation in different environments. Therefore, this paper considers the different interactions between plants when the number and species of plant communities change, and analyzes the viability of plant communities and changes in plant population density under different drought conditions by mechanism.

2. Materials and Methods

2.1. Data acquisition and preprocessing

2.1.1 data acquisition

Rainfall is an important factor in determining the occurrence of drought. Drought occurs when rainfall falls below a certain level. The impact of rainfall on drought varies by region and season. We collected years of daily precipitation data from the China Meteorological Science Data Center in Aksu, Xinjiang.

In addition, to study the relationship between the root lengths of some plants in a community or near a site, we need to collect and sort out the root lengths of plants in desert areas to a certain extent. We used MA Akram et al.[10] and Y Zuo et al.[11] to synthesize and sort out the relevant data of plant studies in desert areas. It is convenient for us to analyze the correlation of community root length.

2.1.2 Data preprocessing

To prevent the impact of missing data values and outliers on problem analysis and model building, we carried out data cleaning on the acquired data, filled in missing values and smooth noise data by multiple interpolation methods, and smoothed or deleted outliers to solve data inconsistency.

2.2. Method introduction

2.2.1 Lotka-Volterra method

In studying the relationship between plant species and individuals, we adopted the Lotka-Volterra model, also known as the predator-prey model, which is an iconic model in ecosystem studies and is often used to explain the changes in the relationship between the number of two parties in an ecosystem. At the heart of the model is the Lotka-Volterra equation, which gives how the population size of predators and prey changes depending on the number and interaction of both parties. In this study, what needs to be studied is the interaction and influence between plants under drought conditions. Lotka-Volterra model can be used to describe the relationship between them, to solve the model.

2.2.2 Runge-Kutta method

Lotka-Volterra equation is a mathematical model composed of differential equations, and the Runge-Kutta method is a very classical and effective method for the numerical solution of differential equations. Runge-kutta method is an important implicit or explicit iterative method for solving nonlinear ordinary differential equations. This method is used to solve the model in this paper, which has better efficiency and accuracy.

3. Model establishment and solution

3.1. Models of direct plant interaction

Considering the interaction between plants and the environment and the relationship between different plants, we obtained a model of plant community density change over time. When we

simulated the drought time model and brought it into our model, the simulated change curve overlapped well with the actual curve.

3.1.1 Environmental influences on plant growth

The environment in which a plant grows has a big impact on its growth, the water, and salt in the soil. Factors such as sunlight and the relationship between plants will have a great impact on the growth and development of plants. Figure 1 is a schematic diagram of the interaction between plants and the environment as well as between plants.

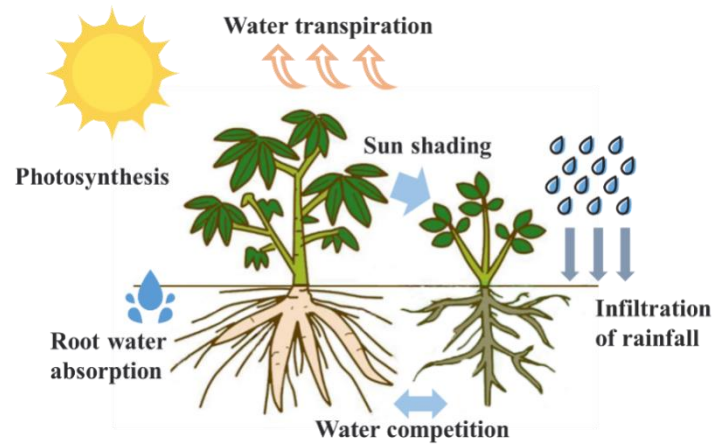


Figure 1. Diagram of plant interaction with the environment

(1) soil water content

To consider the effects of drought on plant communities, we can set soil water content as a variable. Soil water content is precipitation minus evaporation minus the amount of transpiration consumed by plants. We are happy to use the following equation to represent the change in soil water status.

The more water there is in the soil, the faster the water evaporates. So the rate of evaporation is proportional to the water content of the soil.

$$\frac{dE}{dt} = \delta A \quad (1)$$

Where, E is the water consumed by evaporation δ is the evaporation coefficient. The higher the total plant amount, the more water is consumed through plant transpiration.

$$\frac{dT}{dt} = \sum_{i=1}^M \varepsilon_i N_i \quad (2)$$

Where, T is the water consumed by plant transpiration and ε_i is the transpiration coefficient of the i th plant. We assume that the precipitation is directly converted into the soil content and then consumed by evaporation and other forms.

Synthesize the above types:

$$\frac{dA}{dt} = \frac{dW}{dt} - \delta A - \sum_{i=1}^M \varepsilon_i N_i \quad (3)$$

Where A is soil water content and W is precipitation.

(2) Effects of soil salinity and microorganisms

the which many microorganisms in soil can improve soil structure and promote the decomposition of soil organic matter and minerals. Soil microbes that live around plant roots can also regulate plant growth.

The three elements of inorganic salt play a key role in the growth of plants. Inorganic salt containing nitrogen can promote the division and growth of plant cells and make their branches flourish. Inorganic salts containing phosphorus can promote the development of plant seedlings and

flowers, allowing fruits and seeds to mature earlier. Inorganic salts, which contain potassium, strengthen the stalks and facilitate the formation and transportation of starch.

(3) Plants are influenced by their environment

The population density of plants has a saturation level. When the population density reaches a certain number, the growth of this population will be saturated. Meanwhile, since water is the most critical factor restricting plant growth, the saturation value of plant growth is most affected by soil water content, so soil water content is used to calculate the environmental capacity.

Environmental influence coefficient was defined as α_i , indicating the degree of the environment to plant growth, which was proportional to soil water content:

$$K_i = \alpha_i A \quad (4)$$

Where, K_i is the environmental capacity of plants in i , A is the soil water content at time t , α_i is the influence coefficient.

3.1.2 The interaction between species

The number of plant species in an area can affect the interactions between species, and higher species diversity is generally considered to be one of the key factors to improve community stability.

(1) The interaction of plants with water

We believe that water is the main factor affecting the survival of plants in arid areas. Different plants have different capacities for water absorption and water storage, and the capacity of water absorption is often related to plant root length. We can study the effect of plant root length on water absorption intensity to better understand the adaptation mechanism of plants under drought conditions.

If there are plants with different root lengths in a plant community, there will be differences in their ability to absorb water. Plants with longer root systems can better maintain their water uptake requirements under drought conditions, while plants with shorter roots are more susceptible to drought, which can have an impact on the growth and survival of the entire community. Therefore, we believe that the difference in root length between plants is the main factor determining their competition. For example, plants with longer root systems may be more likely to occupy the soil layer with deeper water and nutrients, thus crowding out the growth of other plants. Therefore, it is important to consider the root length of different plants in the plant community for the study of plant competition.

Here we list some common plants in dry areas and their root lengths, as shown in Table 1.

Table 1. Common plants and their root lengths

Plant name	Root length(cm)
Cymbopogon jwarancusa	440
Morus spp	860
Robinia pseudoacacia	150
Populus euphratica	80.5
Tamarix ramosissima	59.7
Artemisia desertorum	35.4
Pinus edulis	170

To establish the relationship between plant root length and water absorption intensity, correlation coefficient analysis can be used. Correlation coefficient p is a statistical index used to describe the linear correlation between two variables, ranging from -1 to 1, where 1 means completely positive correlation, -1 means completely negative correlation, and 0 means no correlation.

Assuming a linear relationship exists between water absorption intensity and root length, the Pearson correlation coefficient can be used to describe the relationship between them. Suppose we have two plants, i and j , whose sample sets of root lengths are I and J respectively.

Pearson correlation coefficient is calculated as follows:

$$a_{ij} = \frac{\text{cov}(I,J)}{\sigma_I \sigma_J} = \frac{E[(I-\mu_I)(J-\mu_J)]}{\sigma_I \sigma_J} \quad (5)$$

Where, $\text{cov}(I,J)$ is the covariance of the sample data, σ is the standard deviation.

When $p > 0$, the root lengths of plants A and B were positively correlated, that is, when the root lengths of plants A and B increased, their water absorption intensity would also increase. When $p < 0$, the root lengths of plants A and B were negatively correlated, that is, when the root lengths of plants A and B increased, their water absorption intensity would decrease. When $p = 0$, there was no linear relationship between root length and water absorption intensity of plants A and B.

Through the correlation calculation of root relationships among the above species, we can study the effect of plant root length on water absorption intensity, and thus better understand the adaptation mechanism of plants under drought conditions. Here we list the interrelationships among several species according to root length, as shown in Figure 2.

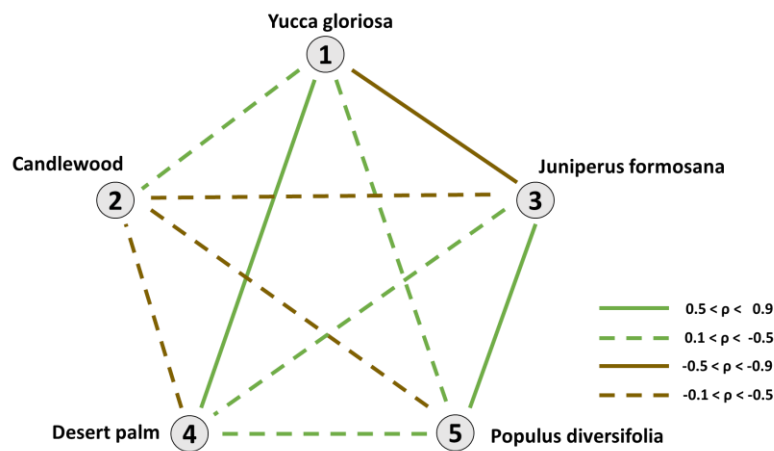


Figure 2. Problems with the food system and our purpose

(2) The interaction of plants in space and air

There is a certain relationship between the height of plants and the amount of sunlight competition. A mathematical model based on photosynthesis can be established to define that the competition relationship is proportional to the biomass of the two plants. The calculation formula is:

$$b_{ij} = \mu_{ij} N_i N_j \quad (6)$$

Where, μ_{ij} is the actual sun shielding degree coefficient of the two plants. b_{ij} is the sunlight competition coefficient of plants.

(3) Integrated plant interaction

After comprehensive consideration of the influence relationships described above, we obtained the following mutual influence relationships among plant species.

$$\rho_{ij} = a_{ij} + b_{ij} \quad (7)$$

The interaction between two plant species can be measured by calculating ρ_{ij} . The greater the number of plant species in an area, the more complex the interaction between species will be. Higher species diversity is generally considered to be one of the key factors to improve community stability and also affect the stability of the entire plant community during drought.

3.2. Model of plant community density over time

We want to build a long-term mathematical model to predict how plant communities will change in different drought cycles. Changes in plant communities are influenced by many factors, including plant interactions, soil nutrition, climate change, and so on.

First, we need to determine the variables to include in the model. In this model, we will consider the following variables:

- (1) Plant biomass
- (2) Interactions between different plant species
- (3) The frequency and intensity of drought
- (4) the growth environment of plants

We can adapt the Lotka-Volterra model to consider the interaction between different plant species. Plant biomass is directly proportional to the inherent growth rate of plants and the difference between plant biomass and environmental tolerance, and is also influenced by the interaction of other plants. We assume that there are altogether M plant types in the environment. So the relationship between the numbers of each plant species is as follows:

$$\frac{dN_i}{dt} = r_i N_i \left(1 - \sum_{j=1}^M \frac{\rho_{ij} N_j}{K_j} \right) \quad (8)$$

Where, N_i represents the number of each plant species, r_i is the inherent growth rate of the i th plant, and K_i is the environmental capacity of the i th plant.

Therefore, considering the above environmental factors such as soil precipitation, soil salinity, microorganisms, as well as the interaction between plants and other comprehensive factors, the change model of plant community density with drought time series was obtained.

$$\left\{ \begin{array}{l} \frac{dN_i}{dt} = r_i N_i \left(1 - \sum_{j=1}^M \frac{\rho_{ij} N_j}{K_i} \right) \\ \frac{dA}{dt} = \frac{dW}{dt} - \delta A - \sum_{i=1}^M \varepsilon_i N_i \\ K_i = \alpha_i A \\ \rho_{ij} = a_{ij} + b_{ij} \\ b_{ij} = \mu N_i N_j \\ a_{ij} = \frac{\text{cov}(I, J)}{\sigma_I \sigma_J} \end{array} \right. \quad (9)$$

3.3. Fourth order Runge Kutta method

3.3.1 Rungekutta solution process

For complex differential equations, we can use MATLAB to solve them. When Runge Kutta method is used to solve differential equations, the accuracy is higher. We improved the Runge Kutta method, and then obtained the results. The specific steps are as follows:

Step1: Fitting parameters. According to the growth data of each plant in the biome, the gradient descent method was used to fit the equations in the model, and the corresponding model parameters were obtained

Step2: Iteration of algorithm. Set the step size $h=0.001s$ traversal length as the growth of plant crops for many years, and calculate k_1, k_2, k_3, k_4 corresponding to the above four first-order differential equations successively according to the recursive formula, and then calculate the corresponding next discrete value y_{n+1} .

Step3: Application of algorithm and solution of model. It is easy to know that N_i is the population density of the i th species, and the corresponding value at the time interval of one day is taken and stored in the result.

3.3.2 Solution result analysis

The data we've collected is daily rainfall over many years in the dry areas, which is somewhere between 50 and 200ml per year. Observations show that precipitation varies greatly from year to year.

According to the amount of rainfall, it can be divided into dry years, normal precipitation years, more rainfall years.

Through the data that annual precipitation is about 50ml to 200ml. Observations show that precipitation varies greatly from year to year. According to the amount of rainfall, it can be divided into dry years, normal precipitation years, more rainfall years. Figure 3 shows the annual precipitation distribution in Aksu Prefecture, Xinjiang.

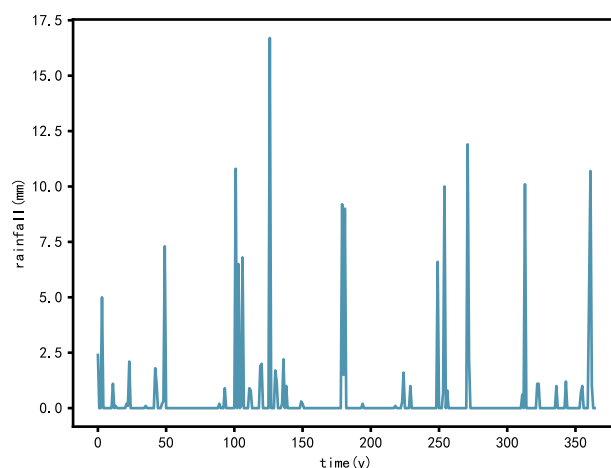


Figure 3. A year of precipitation in Aksu Prefecture, Xinjiang

We analyzed plant growth in desert regions by obtaining data on plant species, plant species density, plant root length, and weather conditions in arid regions. Assuming that the population density of each plant is equal in the initial environment, these parameters are brought into the model to obtain the curve of plant population density over time, as shown in Figure 4.

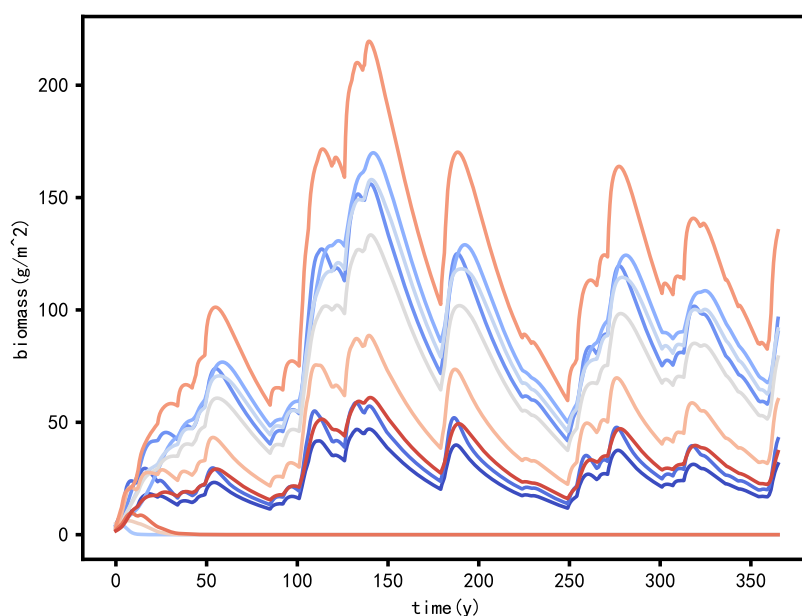


Figure 4. Problems with the food system and our purpose

It can be seen from the image that many plants cannot adapt to the arid environment at the initial input, and the population density of these plants will soon decrease to almost zero, while the population density of the remaining plants will change greatly. It can be found that the plant population increases obviously in the period of rainfall, and then gradually declines after reaching the peak, which reflects the main factor affecting the change of plant population in the arid area during rainfall.

4. Conclusion

The relationship between drought conditions and species viability was analyzed in detail. Prior to the establishment of the model, the paper analyzed the important factors that may affect the drought resistance of species, such as species correlation between different species, light, water, air competition among plants and other parameters. Taking these factors into account, the improved Lotka-Volterra model was established through coupling. Through the display of differential equations to describe the change function of plant growth state with respect to drought, the corresponding mathematical expression is obtained.

In order to explore the rationality of the model, the daily rainfall data of the region was obtained by searching data to measure the local drought situation, and the relevant parameter information of the plant community was obtained. The Runge Kutta method was adopted to solve the numerical solution. Finally, the interaction between different plants before the drought period was obtained, and it was found that the long-term drought would have adverse effects on plant growth. Plant interactions can reduce this effect, and abundant plant populations can grow rapidly after short periods of rainfall, thus improving ecosystem stability. Therefore, it can be seen that there is a mutually reinforcing relationship between plant populations under drought conditions.

References

- [1] Wgii I , Chapter A R , Uk J J . Food Security and Food Production Systems. 2014.
- [2] Allen C D , Macalady A K , Chenchouni H , et al. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests[J]. Elsevier, 2010(4).
- [3] Balint Z , Mutua F , Muchiri P , et al. Chapter 23 - Monitoring Drought with the Combined Drought Index in Kenya[J]. Developments in Earth Surface Processes, 2013, 16:341-356.
- [4] SeyedYahyaSalehi-Lisar, HamidehBakhshayeshan-Agdam. Drought Stress in Plants: Causes, Consequences, and Tolerance[J]. Springer International Publishing, 2016.
- [5] Barros V , Stocker T F . Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change[J]. Journal of Clinical Endocrinology & Metabolism, 2012, 18(6):586-599.
- [6] Qianwen G, Arif M, Zhongxun Y, et al. Plant species composition and diversity along successional gradients in arid and semi-arid regions of China[J]. Forest Ecology and Management, 2022, 524: 120542.
- [7] Rui L I , Liu Y , Zhang K . Plant species diversity of wetland ecosystem in an arid and semi-arid region in northwest China[J]. Frontiers of Forestry in China, 2007, 2(3):284-290.
- [8] Song W, Song R, Zhao Y, et al. Research on the characteristics of drought stress state based on plant stem water content[J]. Sustainable Energy Technologies and Assessments, 2023, 56: 103080.
- [9] Peng L, Xue W, Yu F H. Live under strong power: A third plant species alters interspecific interactions between two plant species[J]. Ecological Indicators, 2023, 146: 109758.
- [10] Akram M A , Zhang Y , Wang X , et al. Phylogenetic independence in the variations in leaf functional traits among different plant life forms in an arid environment[J]. Journal of Plant Physiology, 2022, 272:153671-.
- [11] Zuo Y , Hu Q , Liu J , et al. Relationship of root dark septate endophytes and soil factors to plant species and seasonal variation in extremely arid desert in Northwest China[J]. Applied Soil Ecology, 2022(175-):175.