Research on the Impact of Drought Environment on Plant Community Diversity Based on Differential Equation Models

Wang Li#, Taorui Su#, Zhuoheng Yang*, #

Sichuan University-Pittsburgh Institute, Sichuan University, Chengdu, China, 610065

*Corresponding author:3146034491@qq.com

#These authors contributed equally.

Abstract. Plants play a crucial role in the influence of ecological environment. In order to predict the changes of plant communities in dry weather, this paper firstly collected monitoring data from a sample of grassland ecological stations from the China Biological Research Network (CERN), and constructed a linear model for the changes of plant communities under different climatic conditions, and since the linear correlation of this model was not strong, this paper then constructed a new non-linear correlation model. Firstly, the interspecific competition model of vegetation community was constructed from the interspecific competition model, and then the functional relationship between drought rate and plant growth rate was obtained using the logistic function, and the multi-species competition model was improved. Finally, data from ecological stations were used to visualise vegetation competition and development.

Keywords: plant diversity, differential equations, logical functions.

1. Introduction

As global warming intensifies, the extra heat will cause extreme regional and seasonal temperatures to rise, exacerbating climate anomalies, which leads to desertification of the land. Tropical monsoon climate regions with significant rainfall and dry seasons, along with cumulative global warming, are increasingly devastated by drought disasters. In this process, vegetation communities play a crucial role in addressing global warming and climate anomalies associated with desertification.

In order To predict the change of plant community in dry weather, A number of scholars have contributed in advance to modelling the composition of plant communities in response to extreme weather data. Du Fuzhen quantifies plant richness by modeling the mechanism [1]. Based on field survey data of typical shoal wetland vegetation in Poyang Lake, Xue Chenyang investigated the correlation between community stability and species diversity of the wetland plants at different water stages using an improved M. Godron method, as well as Shannon-Wiener and Pielou indices [2]. Liu Zhenguo and others introduced and compared four representative empirical models representing community dynamics, namely the mosaic circulation model, random wandering model, proportion model of species of the same resource, spatial occupancy model, and their mechanism of action [3]. According to Zhao Yudong, he constructed different plant richness and analyzed the changes of soil fungal community in response to drought and plant invasion in the process of regulating plant diversity [4]. Despite these valuable contributions, previous studies have had some limitations. Existing studies lack a comprehensive multi-species competition model that more realistically reflects ecological interactions. Therefore, this paper addresses these limitations by incorporating species interactions and constructing a new multi-species competition model. In the first step, we made a preliminary estimate of the model, taking into account changes in the drought cycle and interactions between different species during the drought cycle, and incorporating climate impacts, then we developed an assessment and prediction method to analyze the viability of communities and the number and types of species. Our model can then be applied to regions with different geographical conditions, both natural and man-made, to enhance the resilience of vulnerable ecosystems to extreme conditions.

2. Species richness prediction model based on multivariate linear regression equation

Plant competition models are mainly divided into phenomenological models, which only describe the results of competition, and mechanical models, which describe the physiological processes behind plant growth. A study of competition that considers only final output is inevitably limited by the inferences that may be drawn about the competitive process. Quantitative measurement of growth during growth is necessary to understand the changing dynamics of species interactions and elucidate the competitive mechanisms that determine individual growth [5].

In order to model plant community changes under different climatic conditions, we constructed a multivariate analytical model. The independent variables were determined based on the collected data and the relationship between the variables was first analysed. Pearson's correlation coefficient, Spearman's correlation coefficient were used between two variables, and standardised regression algorithm was applied to a pair of variables. More often than not, the analysis was carried out using partial least squares, which was tested using matlab. Based on the results of the analyses, the corresponding multivariate analysis prediction models were constructed for analysing the relationships between different types of variables in irregular weather cycles.

2.1. Multivariate analytical model

2.1.1 Model Preparation

(1) Data Collecting

Due to the large sample size and insensitivity to climate, we selected the 2006-2015 monitoring data from the Biological Research Network for the steppe ecological station, with a complete range of observations, a modest sample size and a long observation period. The data included the composition of plant communities, including sample site names, species' natural height, species diversity and the amount of green present on the species' land. These data sources are summarized in Table 1.

Table 1: Data source collation

Database name	*Data Website*
Cover degree	https://biolres.biomedcentral.com/
Species height	https://biolres.biomedcentral.com/
Number of species	https://biolres.biomedcentral.com/
Species area	https://biolres.biomedcentral.com/

(2) Data cleaning

The data were grouped into 10 groups, and the components of the sample with fewer initial plant populations and a higher annual change rate were selected. For the missing values in the data, we substitute 0. We look only for valid values, take values that vary by only 1 or 2 as outliers, and replace them with zeros to enhance linear relationships. At the same time, we measured the degree of drought in terms of rainfall in order to simplify the model and increase its rationality. According to Figure 1, one of the most important things we found in this process was that the relationship between different pollution conditions and plant habitats and temperature environments was not taken into account. If this factor is not taken into account, many wrong results can occur, such as high average summer temperatures, leading to excessive precipitation, etc.

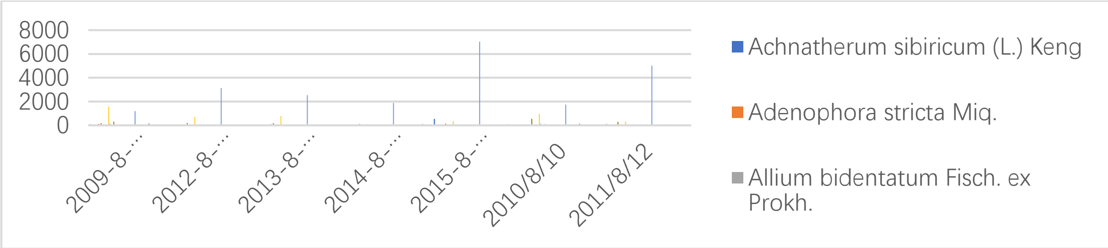

Figure1. Plant data collection tables

2.1.2 Model Establishment

Based on the data, we wanted to design the model with n different species, each with a corresponding measurement at m point in time, so we could represent this data as a matrix x of n row m columns, each representing a sequence of measurements for a species, and each column representing measurements at a point in time.

We used multivariate linear regression equations, using time vectors as independent variables, to predict measurements for each species. In order to consider the interactions between species, we can add the terms of interactions between different species to the model as independent variables. Assuming we use a linear model, the multivariate linear regression equation can be expressed as follows:

$$\mathrm{Y} = \mathrm{b_0} + \mathrm{b_1} \times x_1 + \mathrm{b_2} \times x_2 + \ldots + \mathrm{b_n} \times x_\mathrm{n} + \mathrm{b_{n+1}} \times x_1 \times x_2 + \mathrm{b_{n+2}} \times x_1 \times x_3 + \ldots + \mathrm{b_{n+m}} \times x_\mathrm{n-1} \times x_\mathrm{n} \quad (1)$$

As Christian said the plants in a population are never the same. There may be variations in germination time, local adjacency conditions and microenvironment, leading to size changes. If plant growth is limited by resources that may be monopolized, such as light, then asymmetric size competition may occur, where larger plants will grow faster than smaller plants, resulting in asymmetric size growth [6]. We should take all factors into account.

Of these, Y represents measurements of the target species we are predicting, x_1 to xn represents a matrix of measurements at m time points for n different species, b_0 to $b(n+m)$ represents coefficients in the model, with b0 representing intercept, b1 to bn representing coefficients for each species, and $b\ (n+1)$ to $b\ (n+m)$ representing coefficients for interactions between different species.

2.1.3 Results

According to the linear regression model, the linear equation (1) is calculated as linear equation (2).

$$Y = 0 + 0.6345 \cdot x_1 + 0 \cdot x_2 + 0.9233 \cdot x_3 + 0 \cdot x_4 + 0 \cdot x_5 + 0 \cdot x_6 + 1.0108 \cdot x_7 + 0 \cdot x_8 + 1.3324 \cdot x_9 + 0 \cdot x_{10} + 0 \cdot x_{11} + 0 \cdot x_{12} + 0 \cdot x_{13} + 0 \cdot x_{14} + 0 \cdot x_{15} + 0 \cdot x_{16} + 2.224 \cdot x_{17} + 0 \cdot x_{18} + 0 \cdot x_{19} + 0 \cdot x_{20} + 0 \cdot x_{21} + 0 \cdot x_{22} + 1.4321 \cdot x_{23} + 0 \cdot x_{24} + 0 \cdot x_{25} + 0 \cdot x_{26} + 0 \cdot x_{27} + 0 \cdot x_{28} + 0.9545 \cdot x_{29} + 1.2379 \cdot x_{30} + 0 \cdot x_{31} + 4.7822 \cdot x_{32} + 1.3612 \cdot x_{33} + 0 \cdot x_{34} + 1.0225 \cdot x_{35} + 0 \cdot x_{36} + 1.1646 \cdot x_{37} + 0.1223 \cdot x_1 \cdot x_2 \quad (2)$$

This equation contains intercept and self coefficient and interaction coefficient, but because of the few data and no strong linear relationship, as Figure 2 shown.

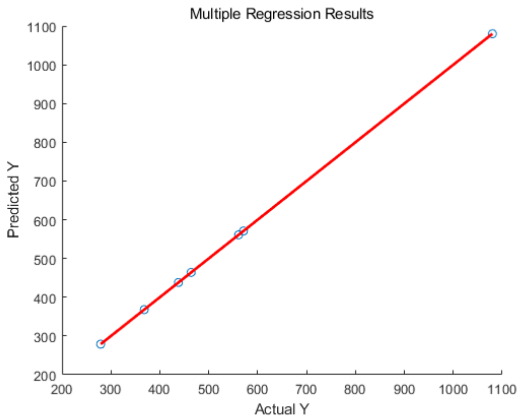

Figure 2. Thinking research paper figure

2.2. Model of differential equations for species competition

For model I, the frequency of available data sampling is generally annualized and data are scarce, as it is difficult to quantify the population of an area on a monthly basis. The results predicted by linear regression model have no strong linear relationship, so we want to try to establish a new nonlinear model. We need to: consider interactions between different plant species; consider the effects of drought on plant communities. A model of ordinary differential equations can be obtained by combining the two functions, both of which are subject to the Logistic Law. These two parts are described separately below.

2.2.3 Model Preparation

(1) Data Collecting

Khambadkone mentioned in his paper that India's climate belongs to the tropical monsoon climate zone [7]. Tropical monsoon climates are hot throughout the year and have rainy and dry seasons. Droughts in tropical monsoon climates have a significant seasonal cycle. The southeastern part of India is a typical tropical monsoon climate region. Therefore, we are targeting an environmental station in a tropical monsoon region of India, covering an area of one hectare. There are four typical plants.

(2) Data Cleaning

Because of the variety of species, to simplify the model, we divided the plant community into three types, trees, shrubs, and herbs, based on the height of their species. Parida mentioned plants typical of tropical monsoonal climates in India, which we selected and analyzed as Table 2 shown [8].

Table 2: Data source collation

Serial number	1	2	3	4
Type	Arbor	Shrubs	Herb	Herb
Species	Banyan	Crape myrtle	Basil	Mint
Number of initial populations (N_0)	100	100	100	100
Maximum annual growth rate (r_0)	0.3	0.5	0.9	0.8
Area required for each plant to grow(S)	12	6	1.5	2
Environmental capacity (K_i)	800	1600	6600	5000

(3) Model Simplification

We simplify the environmental capacity of a plant species to the ratio of the total area of the environment to the amount of space each plant needs to grow, and the total area is a hectare here.

Drought is affected by temperature, precipitation, etc. However, tropical monsoon regions with periodic drought have high temperatures throughout the year, so we can conclude that temperature has little effect on drought. The rainy season has more precipitation and less drought; rainfall is low and drought is high during the dry season.

2.2.4 Model Establishment

(1) The growth of individual species

J-curve:

Suppose there was only one population. Under ideal conditions such as adequate food (nutrients) and space conditions, a suitable climate and no hostile environment, the population growth rate remains constant and the population will continue to grow.

A) The model assumes that, with adequate food and space conditions, a favorable climate, and no hostile environment, the population will increase by a certain number each year, with the second year's population being λ times that of the first year.

B) Modelling: after t population numbers are:

$$N_t = N_0\lambda^t \tag{3}$$

Where N0 is the beginning of the population, t is the time, Nt is the number of the population after t, and λ is a multiple of the population a year ago.

The metabolic theory of ecology focuses on power-law functions because of their ability to predict relationships between many aspects of individual survival and growth [1].

S-curve:

Quantitative evolution of a single population in a limited natural environment is governed by the Logistic Law. For individual species, S-type growth: population size is less than K/2 and population growth rates are still increasing. The population growth rate is biggest when the population size is K/2. The population growth rate decreases when the population is greater than K / 2, at which point the population continues to increase until environmental capacity K is reached. When the population reaches the maximum allowable under environmental conditions and the environmental capacity K, the population will cease to grow. Likely to remain relatively stable at K.

Logistic functions need to be introduced at this point.

$$N(t) = rN\left(1 - \frac{N}{K}\right) \tag{4}$$

(2) The growth of two species

Populations evolve when there is no perturbation of external conditions and environmental capacity exists, accounting only for competition among species. The idea of the control variate method allows us to build the model step by step. Predicting how a vegetation community changes over time does not account for the effects of external conditions such as drought, pollution, habitat and so on. For the moment, we need only consider the role of competition between plants and environmental capacity.

The interspecific competition equation was advanced by Lotka (1925) and Volterra (1926) as a theoretical basis for the interspecific competitive relationship in the 1940s, and has greatly influenced the theoretical development of modern ecology.

When living alone in this natural environment, both populations obey the logistic law of evolution of the population, and it is hypothesized that when they compete with one another they slow the growth of each other's populations, and that the decline in growth is proportional to the multiplication of their population.

An extension of the logistic model is the Lotka-Volterra model of competition between species. The following parameters are defined:

N1, N2: two-species populations, respectively. K1, K2: Environmental capacity for two species, respectively.

r1, r2: Population growth rates of the two species.

According to the logistic model there are the following relationships:

$$\frac{dN_1}{dt} = r_1 \cdot N_1 \cdot \left(1 - \frac{N_1}{K_1}\right) \tag{5}$$

Where: N / K may be understood to be a used space (called "used space item"), then (1-N / K) may be understood as an unused area (called "unused space item")

If two species are competing for or using the same space, the "spatial term in use" should be supplemented by the occupancy of space by N2 populations.

$$\frac{dN_1}{dt} = r_1 \cdot N_1 \cdot \left(1 - \frac{N_1}{K_1} - \alpha \cdot \frac{N_2}{K_2}\right) \tag{6}$$

α: The coefficient of competition between species 2 and species 1 is that each N2 individual occupies the same space as each alpha N1 individual.

Then there is the existence of β: the competition coefficient of species 1 versus species 2, i.e. the space occupied by each N _ 1 individual is equivalent to the space occupied by β N _ 2 individuals. the:

$$\frac{dN_2}{dt} = r_2 \cdot N_2 \cdot \left(1 - \frac{N_2}{K_2} - \beta \cdot \frac{N_1}{K_1}\right) \tag{7}$$

We can summarize the population competition relationship table as in Table 3.

Table 3: Species Competitive Relationship Table

	Species 1 inhibits species 2(K1 > K2/β)	Species 1 inhibits species 2(K1 < K2/β)
Species 2 inhibits species 1(K2 > K1/α)	Both species could win(Result 3)	Species 2 always wins(Result 2)
Species 2 cannot suppress species 1(K2 < K1/α)	Species 1 always wins (Result 1)	Neither species can restrain the other(Result 4: Steady Balance)

(3) The growth of diversity of species

Competitive models of communities of more than two species are now discussed. Each vegetation will be affected by competition from all the other remaining species. Now extend the model to a multispecies competition model, which is a community competition model, and express Formula 2 as

$$\frac{dN_i}{dt} = r_i N_i \left(1 - \frac{N_1}{k_i} - \sum \alpha_k^i \frac{N_i}{K_i}\right) \tag{8}$$

Of these, $r_i$is the growth rate, K_i is the maximum capacity of the species, a species $N_i$to species i competition factor, that is, each N_k individual occupies as much space as α_k^i $N_i$individual.

(4) Multipopulation competitive differential equation model affected by drought

Gavina et al. proposed an Lotka-Volterra competition equation with a nonlinear crowding effect in their paper to analyze the multi-species coexistence problem, which inspired us [9]. We need to establish an expression of the relationship between precipitation and vegetation growth rates. Precipitation is 0 and the growth rate is 0. As precipitation increases, vegetation grows at a greater rate. But beyond a certain value, the increase in precipitation has the opposite effect on the rate of plant growth. So there is a precipitation that is growing at the highest rate, and the image should be S-shaped. This and the growth of individual species we explored through the Logistic function above are very many types. For individual species, S-type growth: population size is less than K / 2 and population growth rate is still increasing. The population growth rate is fastest when population size is K / 2. The population growth rate decreases when the population is greater than K / 2, at which point the population continues to increase until environmental capacity K is reached.

India is a typical tropical monsoon climate region. The rainy season runs from June to September. We can reasonably say that the precipitation rate is 0 and the growth rate is 0. According to this function, the logistic function is constructed, and the modified logical Steely function is obtained by excluding the 0 time value of precipitation.

$$r_i(t) = \frac{L_i}{1+e^{-k_i * h(t)}} - \frac{L_i}{2} \tag{9}$$

Among them, L; is an i maximum growth rate; k, h (t) is precipitation in terms of the rate of growth or steepness of the curve of logical significance. In this paper, The growth rate r in the multi-population competitive differential equation model was replaced by equation 9 to obtain the multi-population competitive differential equation model affected by drought, as shown in equation 10.

$$\left\{\frac{dx_i(t)}{dt} = \left(\frac{L_i}{1+e^{-k_i * h(t)}} - \frac{L_i}{2}\right) x_i(t) \left(1 - \frac{x_i(t)}{N_i} - \sum_{k \neq i} \alpha_k^i \frac{x_k(t)}{N_k}\right)\right. \tag{10}$$

3. Results

We explored the growth of individual species using the aforementioned Logistic function and then analyzed the number of two or more species using the competing Lotka-Voltell a model, which is an extension of the Logistic function. By bringing tabular data into the model, we get individual species populations, populations of two species, populations of multiple species, data over time, and visualize it.

3.1. The growth of individual species

When considering that there is only one species of population growth, we assume that there is only one species of banyan tree. We substitute the data in Table 3 into the formula to obtain Figure 3.

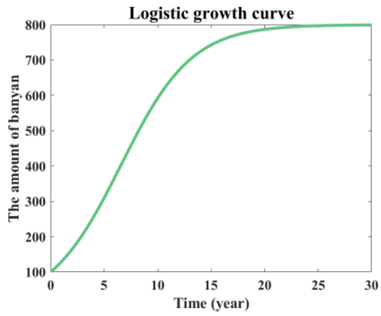

Figure 3. Logistic growth curve

From Figure 4, when environmental resources are limited, the growth curve of the ficus will be s-shaped and will eventually approach the environmental capacity of 800 in the absence of other plants competing with the ficus.

3.2. The growth of two species

We hypothesized that there were only two species at the test site, taking two sets of data from Table 3, banyan and myrtle, banyan and basil, respectively, to represent the model.

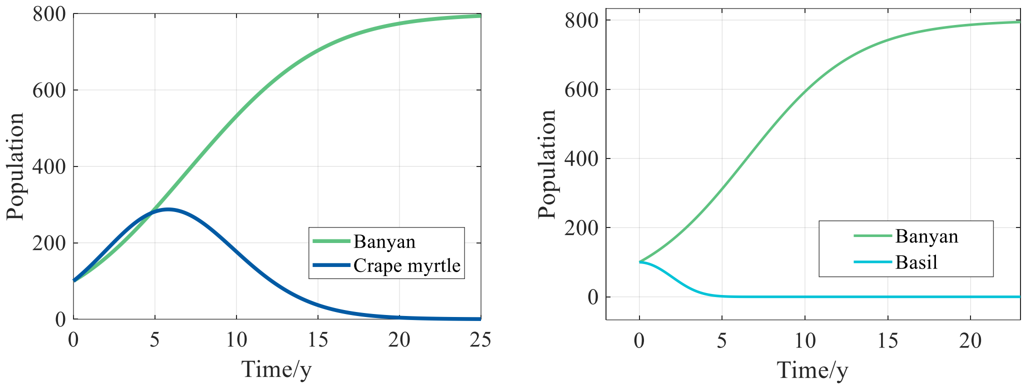

Figure 4. Growth of two species

According to the figure, banyan trees are in a strong position to compete with violets and basil. It will eventually grow to an environmental capacity of 800.

3.3. Growth of multiple species

In validating multiple population growth, we hypothesized that the only species at the test site were banyan, myrtle, and basil. We represent the data in the table to the model of multispecies competitive differential equations, perform calculations, and create Figure 5.

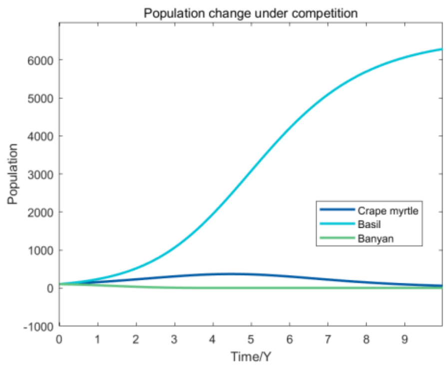

Figure 5. Growth of three species

4. Conclusions

For model I, we collected monitoring data from a sample of steppe ecological stations from the China Biological Research Network (CERN) to construct a multivariate linear regression model.

For model II, the linear correlation of model I is not strong, therefore we choose to construct a new nonlinear correlation model. Tropical monsoon regions have significant seasonal drought cycles, so we targeted plant communities at ecological stations in the region and collected vegetation data. Firstly, the interspecific competition model of the vegetation community was constructed starting from the interspecific competition model, using the logistic function to establish the growth model of individual species. The Lotka-Volterra model, an extension of the logistic model, was then used to model interspecific competition for two species and multiple species. Then the functional relationship between drought rate and growth rate of plants was obtained by logistic function and used to improve the multi-species competition model. Finally, the data from the ecological stations were substituted to visualize the competition and development of vegetation.

References

[1] Du Fuzhen. Response of plant community composition to extreme precipitation events in meadow steppe, Inner Mongolia [D]. Northwest agriculture and forestry university of science and technology, 2022.

[2] Xue Chenyang, Li Xianghu, Tan Zhiqiang et al. Relationship between plant community stability and species diversity in a typical shoal wetland of Poyang Lake [J]. Ecological science, 2022, 9 (02) : 1-10.

[3] Yan Ruirui, Chen Baorui, Zhang Baohui et al. A dataset of plant community characteristics of Leymus chinensis grassland in Hulunbuir (2009-2015)[J]. Journal of agricultural data, 2021, 3 (02) : 75-78.

[4] Zhao Yudong. Regulation of plant diversity on soil fungal community response to drought and plant invasion [D]. Huazhong agricultural university, 2022.

[5] PARK S E, and others. The Theory and Application of Plant Competition Models: An Agronomic Perspective[J]. Annals of Botany, 2013, 92(6): 741–748.

[6] Christian Damgaard, Jacob Weiner. Modeling the growth of individuals in crowded plant populations[J]. Journal of Plant Ecology, 2008, 1(2): 111–116.

[7] K. N K, Prabhukumar M, Nanjundappa M R. Thermal comfort evaluation in architectural studio classrooms – A summer study in a warm to moderate Indian climate[J]. Indoor and Built Environment, 2022, 31(9).

[8] Parida R B, Pandey C A, Patel N. Greening and Browning Trends of Vegetation in India and Their Responses to Climatic and Non-Climatic Drivers[J]. Climate, 2020, 8(8).

[9] Bates D, Maechler M, Bolker B. lme4: Linear mixed-effects models using S4 classes. R package version 0.999375-39, 2011.

[10] A K M G, Takeru T, Kei-Ichi T, et al. Multi-species coexistence in Lotka-Volterra competitive systems with crowding effects.[J]. Scientific reports, 2018, 8(1).