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Study on the effect of irregular weather on plant communities—based on linear regression model

Zhaoxu Yang, Yibo Wang, Lishang Deng

School of Computer and Communication, Lanzhou University of Technology, Lanzhou, Gansu, 730000, China

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Abstract: The frequency and severity of droughts are increasing due to climate change, which poses significant challenges for plant communities to adapt to different climate changes. To predict the effects of unpredictable weather on these communities, this study collected data on temperature, precipitation, evapotranspiration, soil water storage, species number, different species and their types, pollution level, and plant habitat area in Inner Mongolia's Baotou region. A regression model was developed to accurately predict the survival time of plant communities during the dry and rainy seasons, taking into account the interactions between different species, thus accurately reflecting the real ecosystem. This study provides a model to predict the survival time of plant communities, offering new insights into the stability and viability of ecosystems.

1. Introduction

Plants play a crucial role in sustaining life on Earth as they provide oxygen, food, and habitats for various organisms. However, different plant species exhibit varying responses to stress, thereby influencing the overall health and resilience of plant communities.

Among the stressors, drought stands out as a significant factor that is progressively intensifying due to climate change. [1]Determining the ideal number of species required for biodiversity and its localized benefits remains unclear.

Prior research has established that irregular weather exerts various effects on plant communities. Non-precipitation moisture, such as fog and dew, significantly influences the diversity of plant species, particularly within grassland ecosystems. It assumes a critical role in the decomposition of plant litter and the cycling of carbon. Microbial decomposers are impacted differently by distinct types of irregular weather, while humidity also influences decomposer communities.[2] Alterations in irregular weather events prompted by climate change have the potential to modify litter decomposition rates, thereby restricting the development of plant communities through changes in decomposer composition. To comprehensively grasp these effects, additional research is warranted to explore the influence of irregular weather on plant communities under diverse environmental conditions. This knowledge will inform the development of sustainable strategies for ecosystem management.

In order to achieve this goal, we conducted the following work. Firstly, we analyzed and evaluated plants' adaptability under drought conditions, including the study of morphological, physiological, and ecological characteristics. Next, we monitored and measured parameters such as precipitation, evapotranspiration, and soil water content to determine the amount of available water. Then, we determined the severity of the drought and combined it with species adaptability to deduce the mortality rate of species under drought conditions. Based on these analysis results, we established a model equation and used numerical methods for solving to predict the population size of species at future time points. Finally, we validated the accuracy and reliability of the model by comparing it with actual data. Through these work, we were able to gain in-depth understanding of the impact of irregular weather on plant communities and provide scientific basis for ecological conservation and management.   Our work is shown in Figure 1.

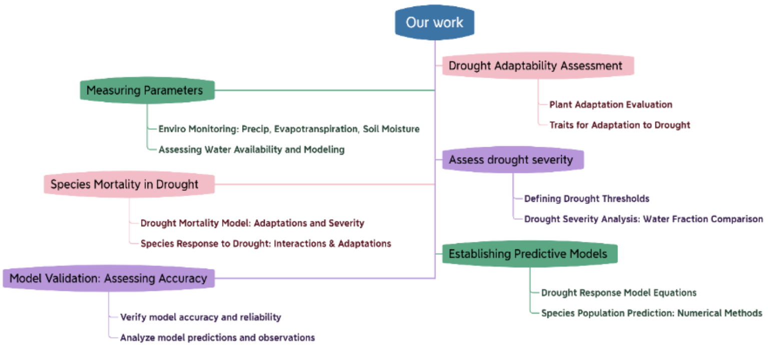

Figure 1: Our job description

2. Species Population Prediction Model

2.1 Data Description

To examine the correlation between drought adaptation and species richness within plant communities, we acquired data on the extent of grassland in each Chinese province, along with corresponding drought severity measurements. These data were visualized as depicted in Figure 2. Subsequently, we specifically chose the Baotou region in Inner Mongolia as our focal area for investigation. The dataset employed in our study encompassed various factors, such as air temperature, precipitation, evapotranspiration, soil water storage, species count, species diversity, pollution levels, and plant habitat size. Primarily, we sourced these data from reputable institutions, namely the Inner Mongolia Meteorological Research Bureau and the Institute of Biology.

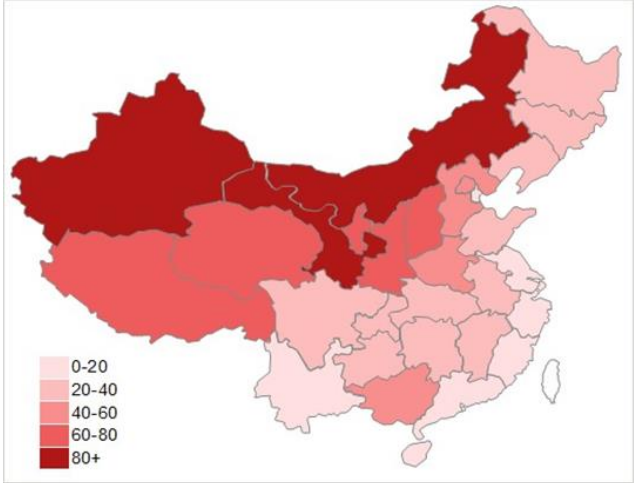

Figure 2: China Drought Level Distribution Map

2.2 Linear model building

Logistic regression, as a generalized linear model, shares many similarities with multiple linear regression analysis. However, the distinction lies in the nature of its dependent variable. While multiple linear regression directly considers the dependent variable as $y = w'x + b$, logistic regression treats $w'x + b$ as the dependent variable through a function L. Specifically, $w'x + b$ corresponds to a latent state p, where $p = L(w'x + b)$, and the value of the dependent variable is determined by comparing the magnitude of p to 1 - p. Logistic regression refers to the case where L is a logistic function, while polynomial regression occurs when L is a polynomial function.

The suitability of multiple linear regression hinges on the dependent variable being a continuous normally distributed variable and exhibiting a linear relationship with the independent variable. If the dependent variable is categorical and lacks a linear relationship with the independent variable, multiple linear regression is inadequate.[3] In such cases, logistic regression analysis, a nonlinear regression method, becomes relevant. It examines the association between the categorical outcomes of the dependent variable (dichotomous or multidichotomous) and specific influencing factors.

Assuming that species numbers in a given natural environment for plant populations adhere to a logistic law, the following model can be formulated. Constructing the model entails comprehending and investigating the population dynamics and ecological adaptations of species under drought conditions. The model-building process can be summarized as follows:

a) Determine the adaptations of species under drought conditions ($w(i)$). This involves analyzing and assessing morphological, physiological, and ecological characteristics to identify biological traits associated with water use efficiency, drought resistance, and other relevant factors.

b) Determine the water availability at time t ($A(t)$), which encompasses precipitation, evapotranspiration, and soil water storage. Monitoring and measuring parameters like precipitation, evapotranspiration, and soil moisture content enable the estimation of water availability.

c) Determine the severity of drought at time t ($D(t)$), reflecting the occurrence and intensity of drought. A threshold value can be established, below which drought stress emerges when the amount of available water ($A(t)$) falls below that threshold.

d) Determine the species mortality at time t due to drought stress ($d(i,t)$), indicating the susceptibility of species to drought conditions. Combining species adaptations ($w(i)$) and drought severity ($D(t)$) allows the computation of species mortality under drought conditions.[4]

Equipped with this foundational knowledge, the model equation can be constructed using the defined variables and their relationships. Numerical methods can be employed to solve the model equation, capturing the population dynamics of species at time t while considering factors like species adaptation, drought stress, and water use efficiency. The process of solving the model entails numerically integrating the model equations with given parameters and initial conditions to determine the population size of species at a future time point. This model-solving procedure can be implemented through a computer program.

2.3 Solution of linear model

To address the differential equations, we employed the Runge-Kutta algorithm within numerical methods. MATLAB offers a convenient built-in function called ODE45 for solving systems of ordinary differential equations, which leverages the 4th and 5th order Runge-Kutta methods for numerical integration. Through simulation, we examined the temporal dynamics of the plant community and investigated the impact of various factors on its long-term sustainability. Additionally, we conducted a comparative analysis between the model's predictions and empirical data to assess its precision and dependability. The model can be expressed by the subsequent differential equation:

$$\begin{cases} \dfrac{dx_1}{dt} = r_1 x_1 \left(1 - \dfrac{x_1}{N_1}\right) - a_1 x_1 \\ \dfrac{dx_2}{dt} = r_2 x_2 \left(1 - \dfrac{x_2}{N_2}\right) - a_2 x_2 \end{cases} \tag{1}$$

or expressed as:

$$\begin{cases} \dfrac{dx_1}{dt} = r_1 x_1 \left(1 - \dfrac{x_1}{N_1} - \theta \dfrac{x_2}{N_2}\right) \\ \dfrac{dx_2}{dt} = r_2 x_2 \left(1 - \dfrac{x_2}{N_2} - \rho \dfrac{x_1}{N_1}\right) \end{cases} \tag{2}$$

In the model equation, the growth rate is denoted by r, and N represents the maximum capacity of the species. Furthermore, θ signifies the competition coefficient of species 2 in relation to species 1, indicating that the space occupied by each individual of species $2\ (N\_2)$ is equivalent to α times the space occupied by each individual of species $1\,(N\_1)$. Likewise, ρ represents the competition coefficient of species 1 for species 2, implying that the space occupied by each individual of species $1\ (N\_1)$ is equivalent to β times the space occupied by each individual of species $2\ (N\_2)$.[5]

To establish the model's parameters, including the species' intrinsic growth rate (r), environmental carrying capacity (k), mortality rate (d), competition coefficient (c), catch rate (h), initial population size (N_0), initial time (t_0), and maximum time (t_max), appropriate values need to be substituted.

The model equation is constructed using an anonymous function that captures the temporal variation in species abundance. It incorporates factors such as the species' growth rate, environmental carrying capacity, mortality rate, competition coefficient, and fishing rate. [6]Moreover, the model accounts for density-dependent effects arising from competition. The model equation is defined as follows using an anonymous function:

$$p = r * N * \left(1 - \frac{N}{K} - c * N\right) - h * N - d * N \tag{3}$$

Utilize the ODE45 function to perform numerical solution of the model equation, yielding the computed time point (t) and the corresponding population size (N).

$$[t, N] = ode45(p, [t_0, t_{max}], N_0) \tag{4}$$

In this study, we provide the ODE45 function with the model equation (p), the time interval $([t\_0, t\_max])$, and the initial population size (N_0). These parameters are passed to the function to enable calculations. Upon execution, the function generates two arrays as output: $'t'$, which comprises the time points at which population sizes were computed, and $'N'$, which encompasses the corresponding population sizes. The dynamic analysis of the number of species is shown in Figure 3.

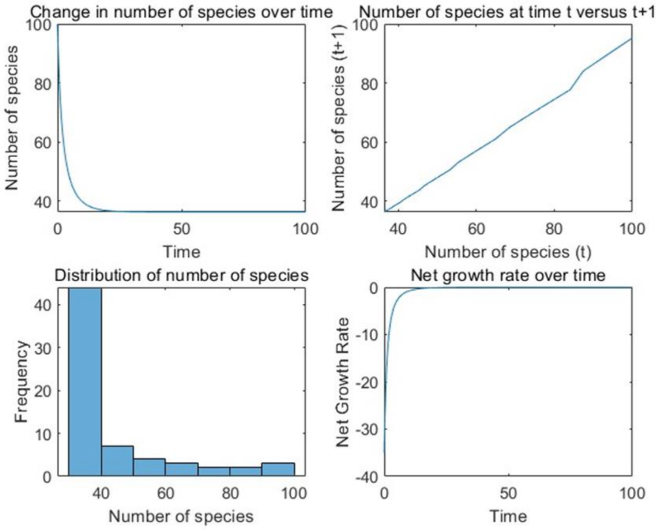

Figure 3: Analysis of the dynamics of the number of species

Furthermore, an alternative 3D solution method exists for this purpose. Initially, the model parameters must be assigned specific values, encompassing the species' intrinsic growth rate (R), the environmental carrying capacity as a percentage (KK), the species' mortality rate (D), the competition coefficient (C), and the harvesting rate (H). Subsequently, the model equations are formulated as a system of ordinary differential equations $(ODEs)$.

$$p = [R * y(1) * (1 - y(1)./y(2) - C * y(1)) - H * y(1) - D * y(1);\ 0] \tag{5}$$

To obtain a comprehensive understanding of the model's behavior, the model equation is solved for various combinations of N_0 and K. [7]This involves solving the equation for each unique pairing of initial population size (N_0) and carrying capacity (K). The resulting data is then used to generate a 3D surface plot, providing a visual representation of the model's dynamics. The population dynamics of the species are shown in Figure 4.

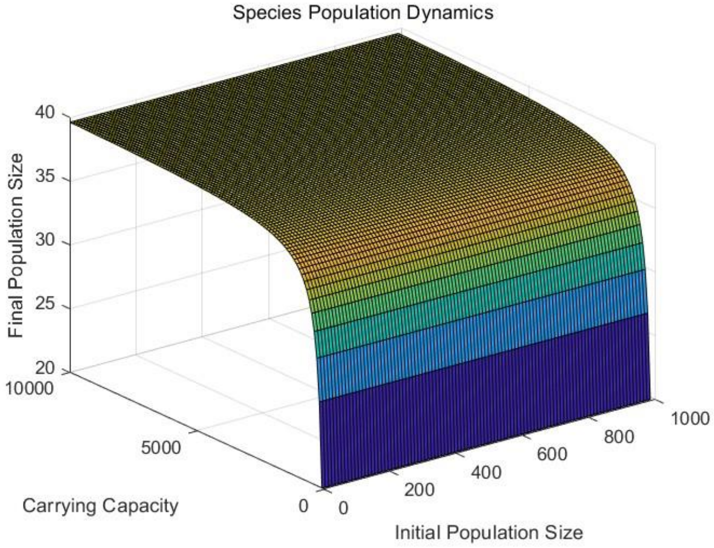

Figure 4: Species population dynamics map

In the subsequent analysis, we explore the influence of environmental factors on plant growth, specifically considering the impact of precipitation (h) on growth rate through photosynthesis. [8]We establish a function with precipitation as the independent variable and growth rate as the dependent variable:

$$ri(t) = k * h(t) \tag{6}$$

From a statistical perspective, the following assumptions can be made:

a) The growth rate (ri) is directly proportional to the amount of precipitation (h), disregarding heavy rainfall in arid regions.

b) Both the growth rate and precipitation can be modeled using logistic functions.

c) In the logistic function, when precipitation is zero, the growth rate is also zero.

d) The maximum growth rate of the species, denoted as Li-species x, can be represented using a logistic function with a parameter k.

Based on the aforementioned assumptions, it is implied that the logistic function for growth rate yields a value of 0 when precipitation is 0. These findings are further integrated with the variable analysis to solve the differential equation model.

Regarding the analysis of variables, a sample size of $N < 5000$ is used, and the Shapiro-Wilk test is employed. The obtained results indicate that the significance P-value is 0.914 for the increment percent sample N, suggesting no significant evidence to reject the original hypothesis. Therefore, the data conforms to a normal distribution.

Similarly, for the precipitation sample with $N < 5000$, the Shapiro-Wilk test yields a significance P-value of 0.400, indicating that the data also conforms to a normal distribution, as the original hypothesis cannot be rejected. The species increment percentage dynamics plotted against the precipitation and growth rate curves are shown in Figure 5 and Figure 6, respectively.

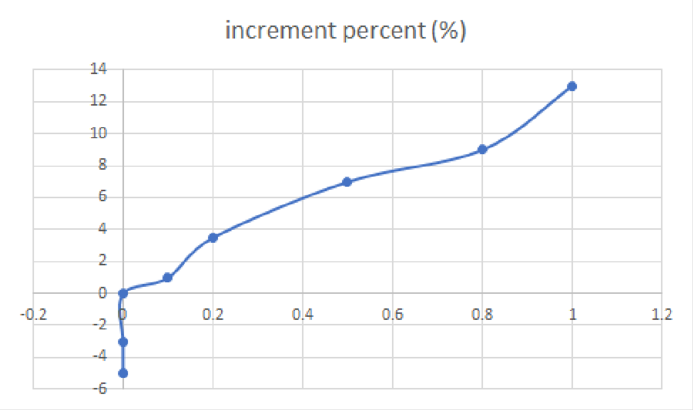

Figure 5: Increment percent dynamics graph

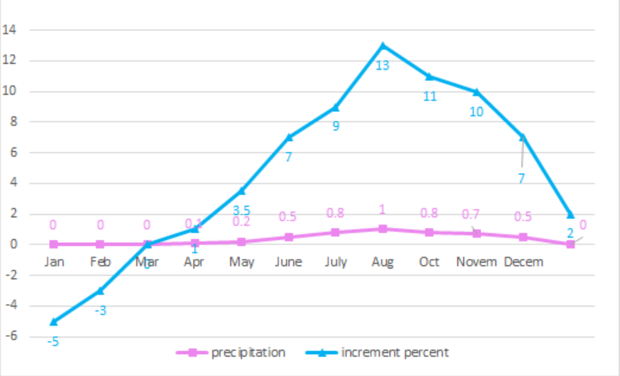

Figure 6: Precipitation and growth rate change curves

The presented graph illustrates the outcomes of the concentration trend analysis, represented as a scatterplot depicting the frequencies of increment percent. Building upon this model, we have the opportunity to apply it to various natural conditions. By assuming the expression for k mentioned earlier, we can substitute it into the equation and determine the curve representing the change in quantity. This allows for further analysis and forecasting of the data.

3. Results

Empirical observations have indicated that plant communities consisting of four or more species exhibit enhanced adaptation to drought conditions. However, our model offers a more comprehensive understanding of this phenomenon. By simulating communities with varying species compositions, we can observe their responses to the drought cycle, potentially uncovering a threshold beyond which additional species no longer confer additional benefits.

Each species possesses distinct tolerances to drought and other environmental stresses. By simulating communities with different species combinations, we can examine how community composition influences their response to the drought cycle. For instance, communities including deep-rooted species may exhibit superior adaptation to drought compared to communities composed solely of shallow-rooted species.[9]

We can also model communities subjected to different drought frequencies and severities. By assessing scenarios with more frequent or severe drought events, we can ascertain whether communities with greater species diversity display improved adaptation. Conversely, in scenarios with less frequent drought occurrences, the impact of species diversity on community resilience may be diminished.

Factors such as pollution and habitat reduction significantly impact the resilience of plant communities. Pollution can influence species' growth rates and mortality, while habitat reduction restricts available space and resources within the community. Incorporating these factors into our model enables us to examine their interactions with the drought cycle and the number of species within the community.

By analyzing our simulations, we can identify strategies to ensure the long-term viability of plant communities. Promoting biodiversity within the community may emerge as a valuable approach to enhance its resilience against drought and other environmental stresses. Additionally, we can evaluate the broader environmental effects resulting from changes in plant communities, such as carbon sequestration, soil erosion, and water availability. [10]These insights can inform policy-making and management measures aimed at safeguarding and restoring plant communities.

4. Conclusions

In conclusion, our study has yielded valuable insights into the relationship between local biodiversity and drought adaptation in plant communities, achieved through the development of a robust mathematical model. The findings underscore the significance of conserving species diversity as a means to enhance the resilience of plant communities in the face of drought conditions. Moreover, the consideration of functional characteristics and species' drought tolerance emerges as a critical factor in the design and management of resilient plant communities. The detrimental effects of pollution and habitat reduction on plant communities further emphasize the necessity for comprehensive conservation strategies. The predictive capabilities of our model offer valuable contributions to informed decision-making regarding future conservation and management endeavors, particularly when addressing the challenges posed by climate change and environmental stressors. Continued research in this field will undoubtedly broaden our understanding and enhance the effectiveness of safeguarding and managing plant communities.

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