Investigating Plant Community Interactions During Drought Periods Based on the Drought Coefficient-Biodiversity Effect Model: A Case Study in Xinyuan County

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Abstract. Biodiversity and ecosystem interactions are a hot topic in environmental science. Since the Industrial Revolution, human activities have intensified the globalization of climate change, leading to changes in precipitation patterns on different continents, among which the exacerbation of drought cycles is one. To investigate the relationship between biodiversity and ecosystems under climate change, a plant species interaction model based on the Drought coefficient and biodiversity effect model is proposed in this study. This model utilized the data collected between 2008 and 2017 from Xinyuan County, China, to quantify the impact of drought on plant communities, determine the growth rate of each species, and investigate how the plant community as a whole change with the interaction among species and drought cycles. The results show that the existence of drought-resistant plants in the community can enhance the adaptability of the region to drought. Furthermore, the transformation of plant communities from competitive species to facilitative species can also enhance the overall drought resistance of the region.

Keywords: Drought Coefficient, Biodiversity, Plant Interactions, Sustainability.

1. Introduction

Since 1950, many land regions have experienced an increase in drought severity due to natural variations in sea surface temperatures. This trend is expected to worsen in the future and poses a potential threat to ecosystems.[1] Aiguo Dai, Xiaodong Song, and their colleagues used the Palmer Drought Severity Index (PDSI) and its variations, along with the EEMD method, to examine drought changes in modern and past climates. Their findings indicate that most of the observed droughts are caused by recent warming, and the percentage of global dry areas (land area) is increasing by approximately 1.74% per decade.[2],[3] Despite the significant threat that droughts pose to ecosystems, biodiversity may reduce their negative impact, potentially promoting a more stable ecological system. [4] Therefore, studying how biodiversity mitigates the adverse effects of droughts through species interactions is critical. [5]

A study by Cameron Wagg et al. demonstrated that increased plant diversity can alleviate the negative impact of drought on experimental grassland ecosystems during seven consecutive summers, indicating that biodiversity enhances the ability of ecosystems to withstand environmental disturbances.[4] However, research by Daijiang Li and Jesse E. D. Miller suggests that a drier climate due to natural variation leads to a reduction in systematic diversity within plant communities, challenging the stability and sustainability of ecosystems under drought conditions. [6] This could affect species complementarity within ecosystems, resulting in decreased productivity and nutrient retention rates among different plant species.[7] Yuxin Chen and Anja Vogel's intergenerational species experiments indicate that species diversity plays a critical role in resisting invasion by non-native species and sustaining ecosystems. It is predicted that even under increased drought frequency in the future, the stable structure of biodiversity will continue. [8] However, it remains unclear how plant communities maintain stable ecosystems through species diversity interactions under drought conditions.

Currently, research on the impacts of drought on biodiversity primarily focuses on precipitation and evaporation processes while neglecting other hydrological processes such as temperature and soil

moisture variations, which may result in an incomplete evaluation of the effects of drought on biodiversity. Additionally, existing studies mainly concentrate on specific drought-prone regions and ecosystems, lacking comparisons among different ecosystems and geographic regions, which hinders the thorough understanding of the impacts of drought on biodiversity. In evaluating species diversity, current quantifiable indicators are too limited to enable effective comparisons and tracking of species diversity across different ecosystems, regions, or time periods. Therefore, this study chooses Xinyuan County, a semi-arid climate region with distinct seasonal characteristics, instead of traditional drought-prone areas, to reveal the general laws of drought impacts on biodiversity and provide more targeted recommendations for ecological conservation and restoration. The "drought coefficient-biodiversity effect model" will be employed in this study to quantitatively analyze the relationship between drought and biodiversity, providing insights into the mechanisms by which drought benefits from the interaction among biodiversity and how to adapt to the continuously changing drought cycles. This will provide a more reliable scientific basis for ecosystems to adapt to drought.

2. Drought coefficient-biodiversity effect model Method

2.1. Drought coefficient

The impact of drought on ecosystems is influenced by multiple factors, including the severity and duration of the drought, as well as environmental factors such as water availability, precipitation, evaporation rate, temperature, solar radiation, and biotic interactions. To study the relationship between the drought index PDSI and ecosystem growth rate, it is necessary to use a predicted drought coefficient based on actual observation data to quantify the impact of drought. While PDSI already incorporates many key factors such as precipitation, temperature, duration, and soil moisture, there may be limitations in directly using PDSI to assess the impact of drought. [9] Therefore, this paper proposes a method to convert PDSI into a drought coefficient to more accurately reflect the impact of drought on ecosystems. The drought coefficient can comprehensively consider PDSI and other environmental variables that may affect the severity of drought, allowing us to more accurately quantify and predict the impact of drought on ecosystems. By introducing the drought coefficient, we can fully utilize the advantages of PDSI while overcoming its limitations in evaluating the impact of drought. The calculation of the drought coefficient is as following.

The range between -6 and +6 is generally considered as the typical range for PDSI values, with negative values indicating dry periods and positive values indicating wet periods. The relationship between PDSI represented by the variable x and Drought coefficient di, can be expressed through linear regression:

$$d_i = -\frac{1}{6}|x| + 1 \tag{1}$$

Since this study focuses mainly on the drought conditions in weather cycles, the positive part of the PDSI can be ignored. Therefore, the linear regression equation can be transformed into:

$$d_i = -\frac{1}{6}x + 1 \tag{2}$$

2.2. biodiversity effect model

The biodiversity effect model primarily focuses on the interactions of plant communities, which can be divided into two categories: intraspecific interactions and interspecific interactions. [10] Interspecific interactions can be described by measuring the biodiversity effect of plant communities. Biodiversity effect refers to the impact of a population with diverse species composition on survival under environmental stress compared to a population with a single species. This effect involves different types of interactions under environmental stress, including competition and facilitation.

According to the Jena experiment, [11] the positive impact of biodiversity on plants during the drought recovery period has been demonstrated. In this recovery phase, the biodiversity effect strengthens the ecosystem's recovery ability by promoting interactions between species. To further elucidate this mechanism, the biodiversity effect can be decomposed into the following components:

2.2.1 Mechanisms of the Biodiversity Effect Model

Based on Tilman David's model of the biodiversity effect, the $\frac{\partial N}{\partial t}$ represents the change of density of an individual species over change of time due to the biodiversity effect. [12] The *N* on the right side of the equation represents the density of this individual species. The density of the species would multiply with the difference of *(cR - d)*. The symbol *c* represents the rate of intake of a specific resource denoted as *R* in density. While the symbol *d* represents the rate of death, the difference of *(cR - d)* would represent the different from growth, due to the differences between individuals' competition and intake rate for the resources in density unit, and the natural death rate of the species. Therefore, multiplying *(cR - d)* with *N*, the density of this individual species, would create the rate of change of this individual species, with respect to time, due to inter-species interactions:

$$\frac{\partial N}{\partial t} = N(\, cR - d) \tag{3}$$

2.2.2 Modifications to the Biodiversity Effect Model

The model proposed by Tilman David provides a good approximation of the species interactions that contribute to the biodiversity effect. However, the model can be improved by introducing a new variable, *S*, to represent the area of the plant community:

$$S \cdot \left(\frac{\partial N}{\partial t}\right)^r \tag{4}$$

The new variable *r* will represent the number of different types of resources that affect plant community growth:

$$\frac{\partial N}{\partial t} = N(\, cR - d)^{\,r} \tag{5}$$

In addition, it is necessary to specify the range of certain variables: *c* and *R*:

$$c > 0,\ R > 0 \tag{6}$$

3. Xinyuan County Experimental Plot Data Analysis

3.1. Data collection

The dataset of plant species composition was established based on the three consecutive surveys of three continuous plots at the Xinyuan County Ecosystem Observation Station between 2008 and 2017, which includes categorical and qualitative indicators based on the classification of species names in woody plant communities. The categorical indicators include three types of plots at different community levels, and the quantitative indicators include the average breast diameter/base diameter, biomass, and plant density of each plant species. Therefore, the indicators constructed in this study to investigate the interactions among plant communities during drought periods are presented in Table 1.

Table 1. Indicators affecting the plant interaction during drought period

Indicator number	Name of indicator	unit
X_1	experimental plot	-
X_2	community level	-
X_3	average breast diameter/base diameter	cm
X_4	biomass	kg/hm^2
X_5	Plant density	plants per hectare

3.2. Data analysis

3.2.1 Drought coefficient

According to the dataset provided, the time period was divided into pre-drought, drought, and post-drought stages. To make it more specific and quantitative, the time periods were changed into numerical values. The pre-drought stage, also known as the initial stage, was set as $t = 0$; the middle point of all changes was set as $t = 1$ for the drought stage; and the post-drought stage was set as $t = 2$.

Based on the quantitative data analysis, two major categories of quantitative data were integrated: time and the intensity of interactions between species. Descriptive statistical analysis of the data indicated an overall trend of reduced growth rate corresponding to the time periods (pre-drought, drought, and post-drought) in the study site. Therefore, using the linear regression model from the sklearn library in Python, the data was fitted, as shown in Figure 1, and a linear regression equation was obtained with a slope of -0.186, as well as Equation (7).

$$y = -0.186x - 0.373 \tag{7}$$

The slope implies a decrease in growth rate, therefore the drought coefficient is calculated as 1-0.186 = 0.814.

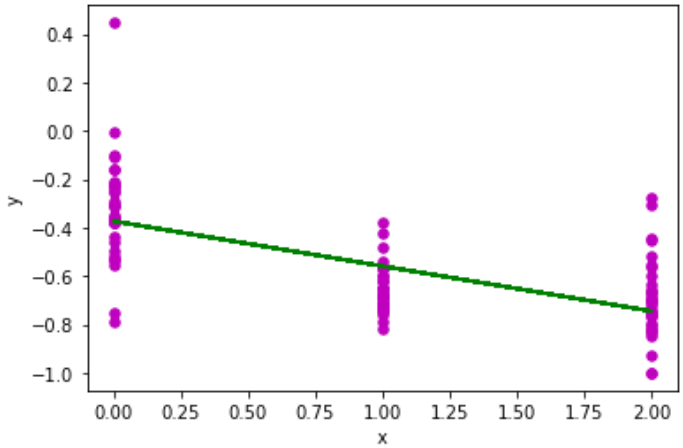


Figure 1. Data fitting linear regression plot

3.2.2 Biodiversity effect model

Considering the need to identify a biodiversity effect model that is applicable to the entire community, rather than solely focusing on the inter-species interactions of a particular individual species within the community, it is necessary to multiply the density change rate, $\frac{\partial N}{\partial t}$, by the area, S, in order to derive the density change rate for the community as a whole, as opposed to that of a single species.

Given that $R > 1$, which means the intake rate of environmental resources other than just one resource needs to be considered, as plants intake more than one crucial resource, such as water, temperature, soil, sunlight, and oxygen. Therefore, to account for the effects of all environmental resources, it is necessary to introduce r as an exponent on the right-hand side of the biodiversity effect model.

The reason for setting $c > 0$ and $R > 0$ is that the rate of resource intake cannot be negative, as it is physically impossible, and the resource density must be greater than zero, as negative resource densities are non-existent, while zero is a possible value. Thus, this perspective on the rate of resource intake at a specified density helps to explain the nature of the biodiversity effect and elucidates the relationship between c, R, and the overall biodiversity effect.

4. Discussion

4.1. Sensitivity Analysis

As the time attribute of the data is categorical, assuming that time is denoted by the values 0, 1, and 2, representing the time periods of pre-drought, during-drought, and post-drought, respectively. Since all drought coefficients are relative values, they have no impact on the results. Therefore, to determine the effects of each variable on the results, it is necessary to calculate the correlation between the time and growth rate coefficients for all four combinations, as presented in Table 2.

Table 2. Pearson Correlation analysis

	mix	mono
ambient	-0.417	-0.51
drought	-0.443	-0.494

Sensitivity analysis is employed to determine how different factors affect the overall growth rate. To examine the linear correlation between datasets under different conditions (i.e., drought or non-drought), manipulating the environmental and diversity factors and calculate the Pearson correlation coefficient. Without accounting for competition, observing that the growth rate is more susceptible to variation in drought conditions due to the greater disparity in correlation, thus highlighting the correlation trend between growth rate and drought in this model.

4.2. Strengths

The model considers various plant interaction factors and simulates reasonable mathematical relationships between each rate of change during the entire integration process. Additionally, the model introduces a parameter for available space, which further accounts for the availability of habitat. Importantly, the model sums up the rate of change between individuals to provide a better description of the biodiversity effect of the entire population.

This approach allows for a greater understanding of how plant populations and communities are influenced by various factors and how these interactions affect their growth and survival. Furthermore, it enables us to analyze the impact of changes in one species on the entire community, providing insight into the overall stability of the ecosystem. Incorporating this aspect into the model is critical for understanding the complex relationships between species and emphasizing the importance of biodiversity conservation.

4.3. Possible Improvements

The drought coefficient is an area where improvement is needed. Despite explaining its construction using influencing factors such as severity and duration, the coefficient was derived from data observations and correlation analysis, rather than a model based on influencing factors. Therefore, a more rigorous approach using influencing factors is warranted. To enhance the model's predictive power, a more detailed investigation of the specific mathematical relationships among resources essential to plant communities, such as water, sunlight, temperature, oxygen, and soil, is needed. Such an approach will provide a more comprehensive understanding of the factors that influence plant growth and survival under conditions of drought.

5. Conclusion

This study has gathered data on plant species composition and relevant indicators through three consecutive surveys of three plots located in Xinyuan County, Xinjiang, China, carried out between 2008 and 2017. The collected information encompasses a variety of aspects such as community-level characteristics, biomass, and plant species distribution density. By utilizing the Drought Coefficient-Biodiversity Effect model, a comprehensive quantitative analysis was conducted to investigate the impact of drought on plant communities. Furthermore, leveraging the Biodiversity Effect model enabled determination of the growth rate of each individual species and the changing dynamics of their interactions throughout the drought cycle. Based on the experimental results, the following conclusions were drawn:

(1) Based on the Palmer Drought Severity Index (PDSI) hypothesis, the coefficient for the range of 1-1.99 was hypothesized to be between 0.833 and 0.667. The data-analysis model produced a coefficient of approximately 0.814, indicating that the actual coefficient falls within the hypothesized range. These findings provide evidence supporting the accuracy and validity of the PDSI hypothesis, and have implications for future research on the impact of drought on plant communities.

(2) The study found that the biodiversity effect exerted a significant influence on the growth rate of plant communities under drought conditions. Specifically, during the recovery phase of the drought cycle, the consolidation property of the biodiversity effect led to better growth in plant communities consisting of facilitative species, compared to those composed of competitive species. Conversely, competitive species lowered the resource intake parameter, resulting in a negative coefficient for the density parameter and negatively impacting growth. These findings highlight the importance of biodiversity in promoting the resilience of plant communities, and have important implications for conservation and ecosystem management strategies.

(3) When the resource intake parameter (cR) is less than the death rate (d), the resulting negative value of (cR-d) would cause a decrease in the density of the species and could lead to a negative growth rate of the plant community. This effect is especially pronounced when the density parameter N is multiplied by (cR-d), as a decrease in N could further exacerbate the negative impact of the negative coefficient. This finding suggests that the interaction between the resource intake parameter and density parameter is a crucial determinant of the growth rate of plant communities under drought conditions, and should be carefully considered in conservation and ecosystem management strategies.

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