Exploring of Diverse Plant Communities and Adaptation to Drought Conditions Based on Advanced Logistics Model with Variable Growth

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Abstract. Bio reciprocal symbiosis is very common in nature, such as soybeans providing food for rhizobia, which uses atmospheric nitrogen to synthesize nitrogen to provide nutrients to soybeans. This paper proposes an advanced Logistic model that adjusts to changes in precipitation and an environmental capacity parameter that varies with the level of symbiosis. The aim is to precisely depict the symbiotic relationship between plants and the interplay among symbiosis, competition, and independent growth of each population in the plant community, as precipitation changes by adapting finite difference method and tertiary Hermit interpolation. The model in this paper offers a comprehensive understanding of how plant populations interact with one another, providing valuable insights into the dynamics of plant growth and development. This paper finally finds that a combination of woody and herbaceous plants had the highest growth rate and total biomass, while herbaceous-only plants required 7 times longer to reach environmental capacity. This paper also reveals that irregular weather patterns, and different levels of species biomass can have different impacts on the recovery time of plant communities after drought or damage, and different types of pollution can have various effects on the community's regeneration, while the effect of overgrazing is the smallest.

Keywords. Logistic model, finite difference method, tertiary Hermit interpolation.

1. Introduction

It has been presented a significant number of observations regarding plant communities, which proposes that diverse species play an essential role in how a plant community responds to stresses, such as a drought adjustment over progressive generations. These observations are grounded on that different species of plants display distinct reactions to stresses. In some plant communities comprising only one type of plant, the generations that follow are not as well adapted to drought conditions as the individual plants in communities with four or more species. However, these observations raise numerous researches questions, including the minimum number of species required for a plant community, the reasons for its expansion, and its implications. To explore and comprehend this phenomenon, this paper will investigate the key factors that affect

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plant communities during droughts. This investigation will be based on considering the relationship of drought adaptability with respect to the number of species in a plant community.

Several researchers have made significant contributions to exploring the relationships between plant communities and drought environments. In this regard, "XI Changbai" and "CHI Yao" etc provides a comprehensive review of population dynamic models and their future developments [1]. "HUANG Li-zhuang" proposes a mathematical model of mutual coexistence of two species, which includes practical mathematical formulas such as the Routh Hurwitz criterion and Bendison judgment method [2]. Furthermore, "WANG Min" and "SU Yong-Zhong" provides detailed data on the allocation of above- and below-ground biomass, which accurately depicts the allocation patterns of biomass in desert grasslands [3]. “A. Gupta”, “A. Rico-Medina” reveal the mechanism behind responses by typical plant species under drought conditions [4]. “C. Vazanna” and “M. R. Colom” aim to evaluate the resistance to water stress of three varieties of perennial grass by multiple experiments measuring data including average height and number of stems per plant [5]. “B. Diwediga” investigated the diversity and patterns of wild landscapes in relation to ecological factors, human disturbances and land protection regime [6]. “YANG Qi” analyzes the stability and diversity under different circumstances of water-salt gradients [7]. “MA Ping” utilized spatial-explicit individual-based models to assess numerous factors on the stability of spatial patterns of different plant species [8]. These studies offer a wide range of ideas, sources, and data that can be utilized in this paper.

This paper proposes a model to predict changes in plant communities over time when exposed to random weather cycles and investigates the impact of different species types and drought cycles. The study utilizes an advanced Logistic model, with practical improvements to enhance its reliability. The second section analyzed various aspects related to the growth of plant communities, including the simulation of irregular weather conditions, the determination of the optimal number of species, and the effects of environmental factors.

This paper concludes that policies such as habitat pollution control, afforestation, and the land conservation is necessary for the long-term sustainability of plant communities. The third section analyzes key factors based on collected data and methods provided in the previous section, and the last section draws a conclusion from the entire discussion, with suggestions for improvements.

2. Methods

This paper explores various aspects of plant community growth, including the simulation of irregular weather conditions and the use of piecewise tertiary Hermit interpolation to establish the symbiotic relationship between plants. The study investigates the growth rate, total biomass, and symbiotic intensity of different plant communities by gradually adding species, with the best benefits observed in communities with 5 species. The effects of environmental factors on herbaceous plant growth were analyzed by using the high-precision finite difference method. The paper concludes that habitat protection, afforestation, and land conservation policies are crucial for the long-term survival of plant communities.

This paper makes several assumptions in order to simplify the model. These include uniform soil fertility, consistent growth rates and biomass, reciprocal symbiotic relationships, no herbivore destruction, and even distribution of plants. These assumptions provide a simplified model for studying the impact of various factors on plant communities.

Firstly, the precipitation is calculated using random algorithm, and the inherent growth rate is calculated based on the precipitation. Then, the population growth rate is calculated. Then, the population growth rate is modified according to the pollution situation, and finally, population biomass is updated.

2.1. Improved Logistics model

In response to the existing problems, this paper proposes a plant mechanism model to depict the interaction not only between plants and plants but also between plants and the changing weather respectively [3].

This paper uses the annual growth of biomass (the mass of the species) to calculate the rate of annual growth which is shown in the following equation [4]:

$$v_t^{(k)} = \frac{m_t^{(k)} - m_{t-1}^{(k)}}{m_{t-1}^{(k)}} \times 100\% \tag{1}$$

In this equation, m_t is the biomass of the species in the sample area in t-th year, m_{t-1} is the biomass of the species in t-1-th year.

To assess the drought stress of plants, the drought intensity is determined by considering the annual precipitation. Following this, six distinct woody and herbaceous plants were selected from the savannah region of Namibia, Africa, each with varying levels of drought tolerance. To save pages, the following K1~K6 is on representatives of each plant.

The annual growth rate of plant biomass is related tightly to precipitation and the degree of symbiosis between plants is related to the proportions of different plants.

The reason for this growth rate that varies with precipitation is when plants are facing with drought stress, the guard cells around the stomata on the leaves are dehydrated and contracted to reduce the stomatal opening, which in turn can contribute to the reduces of the rate of water loss [4].

From this, this paper proposes a Logistics model to measure the relationship between the growth rate and precipitation:

$$v_t^{(k)} = \frac{v_{max}^{(k)}}{1 + a_1^{(k)} e^{-a_2^{(k)}(h - a_3^{(k)})}} - \frac{v_{max}^{(k)}}{2} \tag{2}$$

In this equation, v_{max} is the maximum growth rate of the *k-th* plant under the most beneficial conditions (temperature, humidity etc), h is the precipitation, $a_1^{(k)}$, $a_2^{(k)}$, $a_3^{(k)}$ are the coefficients to be fitted for the plant.

From those figures and equations above it can be inferred that if the precipitation is insufficient, the growth rate is below 0, which can be understood as the plant is gradually withering and dying, and the growth rate becomes 0 when the minimum precipitation requirement is reached. However, because of the excessive precipitation, the plant roots will be supplied with insufficient oxygen and then wither, so the plant growth rate will not increase infinitely with the increase of water volume.

Based on formula (2), the following improvement is proposed:

$$v_t^{(k)} = \frac{a_5^{(k)} v_{max}^{(k)}}{1 + a_1^{(k)} e^{-a_2^{(k)}\left(h - a_3^{(k)}\right)}} + \frac{a_5^{(k)} v_{max}^{(k)}}{1 + a_1^{(k)} e^{a_2^{(k)}\left(h - a_3^{(k)} - a_4^{(k)}\right)}} - \frac{3 v_{max}^{(k)}}{2} \tag{3}$$

Equation (3) exhibits a growth rate that aligns with equation (2) during periods of low precipitation. However, a further increase in precipitation beyond the optimal point will result in a decrease in growth rate. Therefore, $a_4^{(k)}$ is utilized to determine the optimal precipitation value point. As the optimal precipitation value point is lower than the monotonically increasing function when the two functions are superimposed, $a_5^{(k)}$ is introduced to account for this disparity.

A model was developed to consider the symbiotic relationship between precipitation and plants. The classic population growth model in the biological world, known as the Logistics model, was used to infer the following equation:

$$\frac{dm_t^{(k)}}{dt} = v_t^{(k)} m_t^{(k)} (1 - \frac{m_t^{(k)}}{M^{(k)}}) \tag{4}$$

Given that symbiotic relationship is complex and non-linear, it is necessary to modify equation (4) as follows:

$$\frac{dm_t^{(k)}}{dt} = v_t^{(k)} m_t^{(k)} [1 - \frac{m_t^{(k)}}{M^{(k)} + \sum_{i=1}^{6} \left(\beta_1^{(i)} m_t^{(i)2} + \beta_2^{(i)} m_t^{(i)}\right)}] \tag{5}$$

In this equation, $\beta_1^{(i)}$and $\beta_2^{(i)}$are the data to be defined.

2.2. Plants benefiting

This paper provides a definition of "plants benefiting from communities" as follows: Firstly, plants can survive without experiencing death or extinction due to drought. Secondly, in a symbiotic environment comprising multiple plants, a plant can achieve a greater growth rate and the vegetation cover than it could if it was to survive independently.

When herbaceous and woody plants grow together, woody plants shade herbaceous ones during half of the sunshine time. This reduces herbaceous plants' water evaporation rate and increases their water retention rate, enhancing their drought tolerance. The experiment in Namibia showed that herbaceous plants grew twice as fast when not in the shadow of woody plants due to even shading. However, the growth rate did not increase when herbaceous plants were shaded by woody plants.

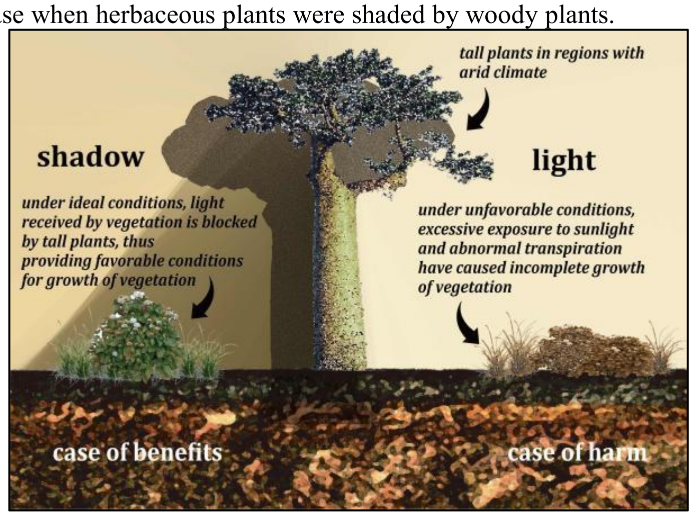

Figure 1. Schematic diagram of woody plant shading to herbaceous plants.

As is shown in Figure 1, herbal plants spend half of the day under the shade of trees, breaking through the constraints of water loss and achieving a greater growth rate than usual.

Assuming that there are 12 hours of daytime and night time, the growth rate in daytime with being shadowed by wooden plants equals to ones with 18 hours of sunlight without being exposed to shadow, which means that the total daily growth rate equals to 1.5 times of the initial value.

To ensure that the herb receives the necessary shade from surrounding woody plants, the amount of shade provided by each plant based on the projected area of its stems and leaves is calculated. This information is crucial because the herb will only benefit from shade provided by woody plants, and accurate calculations help us to optimize growing conditions:

$$\begin{cases} G^{(k)} = 1, & k = 1,2,3 \\ G^{(k)} = \max\left(0, \dfrac{S^{(k)} - S^{(wd)}}{S^{(k)}}\right) + 1.5\dfrac{S^{(wd)}}{S^{(k)}}, & k = 4,5,6 \end{cases} \tag{6}$$

In this equation, S^{wd} means the shadow area of tree canopy projection of wooden plants, $G^{(k)}$ represents the gain coefficient of the k-th plant (herbs only). Combining formula (5) and formula (6), formula (7) can be obtained as following:

$$\frac{dm_t^{(k)}}{dt} = G_t^{(k)} v_t^{(k)} m_t^{(k)} \left[1 - \frac{m_t^{(k)}}{M^{(k)} + \sum_{i=1}^{6} \left(\beta_1^{(i)} m_t^{(i)2} + \beta_2^{(i)} m_t^{(i)}\right)}\right] \tag{7}$$

2.3. *The influence of human factors*

Various human-induced factors that can lead to changes in plant communities were gathered. From these factors, three representative pollution indicators were chosen to quantify the level of pollution. The selected indicators are as follows: heavy metal contamination (u=1) reduced 42.1% environmental capacity, overgrazing (u=2) leads to 15.09% growth rate reduction while excessive logging (u=3) lead to 22.15% quantity reduction.

Formula (8) is proposed as a solution to address the environmental issues caused by heavy metal pollution, overgrazing, and over-cutting. These factors have negative impacts on the environment, including reduced environmental capacity and slowed plant growth rates. Over-cutting can also directly reduce plant biomass. Therefore, formula (8) provides a potential way to mitigate these environmental problems:

$$\begin{cases} \widehat{M^{(k)}} = P_u M^{(k)}, \ u = 1 \\ \widehat{\dfrac{dm_t^{(k)}}{dt}} = P_u \dfrac{dm_t^{(k)}}{dt}, \ u = 2 \\ \widehat{m_t^{(k)}} = P_u m_t^{(k)}, \ u = 3 \end{cases} \tag{8}$$

In this equation, $\widehat{M^{(k)}}$, $\widehat{\frac{dm_t^{(k)}}{dt}}$, $\widehat{m_t^{(k)}}$ are the environmental capacity, growth rate, and biomass after pollution. This formula needs to be combined with formula (7) to obtain the pollution simulation model.

3. Results and analysis

3.1. Plant community development

Over the past nine decades, the dry mixed grass prairie landscape throughout North America has been dramatically transformed by human activities such as agricultural expansion, urbanization, and oil and gas operations. These activities have caused severe damage to the natural ecosystem, posing a significant challenge for the land reclamation and range management efforts [9]. The once-thriving prairies have been fragmented, degraded, and depleted, resulting in a loss of biodiversity and ecological imbalance. The adverse effects of human activities on the prairie ecosystem highlight the urgent need to prioritize conservation and restoration efforts to protect and restore this crucial habitat for wildlife and plant species.This paper set the initial species type as: woody-herbaceous combination, herbaceous-only, woody-only.

When considering herbaceous plants alone, they face greater rates of water loss due to the lack of shelter from woody plants. Additionally, herbaceous plants have poor water retention capacity, which greatly enhances their symbiotic effects, such as significant increases in K4 biomass. However, this increase is short-lived and soon reduces to the environmental capacity. The time required for the entire population in the community to grow to environmental capacity is about 7 times longer than the other two combinations, which takes approximately 14 years.

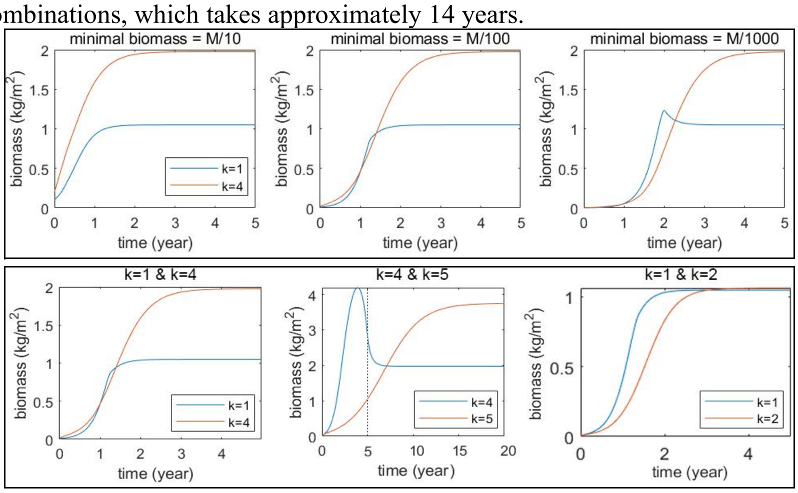

Figure 2. Plant community development under three species combinations.

As is shown in Figure 2, when herbaceous and woody plants grow alone, their growth rate is not as fast as when they coexist. From left to right, woody-herbaceous combination, herbaceous-only, woody-only, it is not difficult to see that the growth rate and environmental capacity of the two has not changed much in the case of only woody plants, and the total biomass is also less.

In contrast, when woody and herbaceous plants are paired together, the growth rate of both is similar, and the shading effect of woody plants improves the growth rate of herbaceous plants. The environmental capacity is reached in just two years, and herbaceous plants can better utilize space, allowing them to fully utilize nutrients and water that cannot be absorbed by woody plants. As a result, the total biomass of the combination exceeds that of only woody plants.

3.2. Changes in plant communities

Abrupt changes are characterized as significant and sudden alterations in the average value of a system's variable or its variability that occurs within a short period of time [10]. Model in this section follows equations (3) and equations (7) to simulate the response of plants to different drought frequencies.

When exposed to irregular weather, due to the increase of precipitation, the natural growth rate $v_t^{(k)}$ first increases to the optimal precipitation value point, because the air-water ratio of the soil is too low, resulting in insufficient oxygen supply necrosis with the root system, so it decreases, and under the cycle of drought and humid climate cycle, the plant growth rate continues to increase and decrease, so the time required to reach its own maximum environmental capacity will also be extended.

Changing the initial biomass of different species in this community simulates the impact of species number on the overall population, and at the same time simulates the recovery of the community after being damaged by different degrees of drought, it is not difficult to see that after the increase of the drought cycle, population recovery takes about 2 years, but the recovery time of communities with higher initial biomass is shorter and that of communities with lower initial biomass requires longer recovery time.

3.3. Plant community development

Overgrazing can have a significant impact on herbaceous plants, but due to the small impact on woody plants and their reliance on shading, the biomass of herbaceous plants can ultimately recover to their environmental capacity [11].

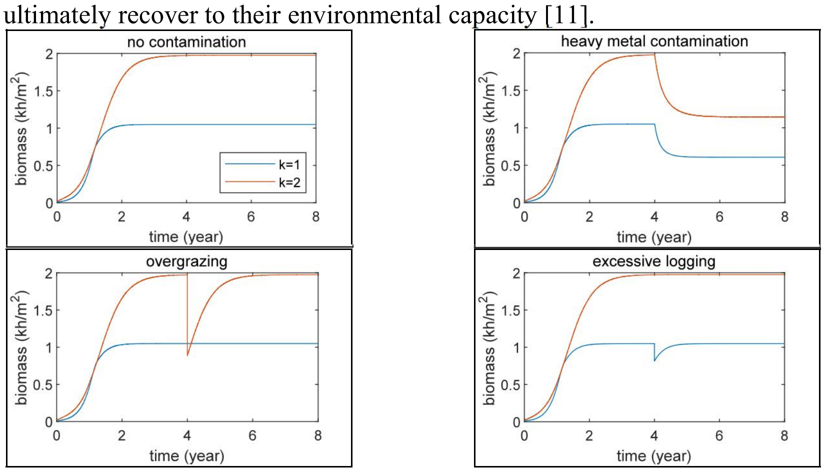

Figure 3. Biomass of plant community under different types of damage.

As is shown in Figure 3, different pollution causes different damage to plant community. The four patterns in Figure 3 depict the biomass trends of plant communities under four different types of human-induced disturbances: no pollution, heavy metal pollution, overgrazing, and excessive logging. Overgrazing has a smaller impact on plant communities and soil components compared to heavy metal pollution and over-cutting. Herbaceous plants are mainly affected, but they can recover quickly due to the sheltering effect of woody plants. Heavy metal pollution damages the soil structure and weakens the land's ability to supply plant nutrients, leading to longer regeneration times. Over-logging targets slow-growing woody plants, resulting in slower recovery times.

4. Conclusion

Diverse plant communities are crucial in responding to stresses like drought. Communities that have multiple species are more adaptable compared to those with only one type. However, questions remain about the minimum number of species needed and its implications. To address this, this paper proposes a model that predicts changes in plant communities over time when exposed to weather cycles and interactions. What's more, this research investigates the impact of growing species and different types using the Logistic model with improvements for reliability and validity. The importance of biodiversity and conservation efforts is highlighted in this paper to ensure the survival of plant communities in the face of increasing environmental stresses. This paper provides valuable insights into the factors affecting plant communities during droughts and offers a practical tool for predicting changes in plant communities over time. Policymakers and conservationists can utilize this method in developing strategies to protect plant communities and promote their long-term sustainability while also identifying the conditions under which plant symbiosis is most likely to occur. Overall, there are many exciting areas of this research in plant symbiosis that could provide important insights into the mechanisms of plant symbiosis and inform the development of new strategies for promoting the establishment of symbiotic relationships between plants in different environments.

References

[1] XI Changbai, CHI Yao, QIAN Tianlu, et al. Animals population dynamic models: a review and outlook. *Ecological Science* **38** (2019), 225-232.

[2] HUANG Li-zhuang. Qualitative Analysis on Mutualistic Coexistence of a Class of Two Species. *JOURNAL OF GUANGXI NORMAL UNIVERSITY FOR NATIONALITIES* **32** (2015), 5-8.

[3] WANG Min, SU Yong-Zhong , YANG Rong, et al. Allocation patterns of above- and belowground biomass in desert grassland in the middle reaches of Heihe River, Gansu Province, China. *Chinese Journal of Plant Ecology* **37** (2013), 209-219.

[4] A. Gupta, A. Rico-Medina, A.I. Cano-Delgado. The physiology of plant responses to drought. *Science*, **368** (2020), 266-269.

[5] Colom M R, Vazzana C. Drought stress effects on three cultivars of Eragrostis curvula: photosynthesis and water relations. *Plant Growth Regulation* **34** (2001), 195-202.

[6] Badabate Diwediga. Landscape Patterns and Modelling of Soil-Vegetation Relationship and Related Ecosystem Services to Support Landscape Conservation in the Mo River Basin, Kwame Nkrumah University of Science and Technology, Ghana, 2016.

[7] YANG Qi. Stability of typical desert plant populations, communities, and ecosystems under water-salt gradients. Xinjiang University, China, 2019.

[8] Ma Ping. Modelling the effects of different modes of positive interactions on plant population dynamics, Northwest University, China, 2019.

[9] Soulodre Etienne M.J, Dhar Amalesh,and Naeth M. Anne. Plant community development trends on mixed grass prairie well sites 5 years after reclamation. *Ecological Engineering* **179** (2022), 106635.

[10] Bagheri, Reza, et al.Climate-driven abrupt changes in plant communities of desert and semi-desert region. *Theoretical and Applied Climatology* **146** (2021), 331-348.

[11] Abdelsalam Mohammed Ibrahim. Effects of Overgrazing on Rangeland Resources in Semi-arid Areas and Rangel and Management: A review Article. *Agrica* **10** (2021), 144-151.