The Prediction Model of Plant Population Dynamics in Semi-arid Regions: A Case Study in Inner Mongolia

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Abstract: Different species of plants have different responses to environmental stresses such as irregular weather, pollution, and human activities. This paper studies plant species changes and atmospheric monitoring data in Xilin Gol grassland, Inner Mongolia, China, and establishes a model to predict plant population changes based on the internal growth of plant communities, species interactions, and external environmental influences. Pearson correlation analysis method was used to verify the model, and the results showed that the model operation results were highly correlated with the actual data. The study found that: 1. Increasing the diversity of community plant species can effectively weaken the impact of irregular weather; 2. The increase in the number of species will lead to an increase in community viability, and that all 12 species of plants are most beneficial to the growth of the community. However, as the number of species continues to increase, the growth rate of community viability will decrease. The prediction model is also applicable to areas susceptible to irregular weather and provides new ideas for studying plant community dynamics.

1. Introduction

1.1 Research Background

Globally, plants show diversity in their responses to environmental stresses such as climate change, pollution, and human activities. These stress factors will inevitably have an impact on the structure and function of plant ecosystems, thereby affecting the stability of other ecosystems. Especially in semi-arid areas, the quantity and structure of plant communities play a crucial role in the recovery and stability of ecosystems.

This study aims to establish a model that can predict plant population changes by studying changes in plant species and monitoring atmospheric data in the Xilingol Grassland, Inner Mongolia. The model will consider factors such as internal plant populations, species populations, and external environmental influences, in order to provide new ideas and methods for studying plant community dynamics in semi-arid areas.

1.2 Literature Review

Maestre et al. (2012)[1] observed a strong correlation between plant species richness and ecosystem multifunctionality through field investigations conducted in arid regions worldwide. In their study of alpine meadows on the Qinghai-Tibet Plateau, Liu et al. (2023)[2] illustrated the significant impact of drought on plant community composition and diversity. Sala et al. (2012)[3] delved into the enduring effects of precipitation fluctuations on primary productivity through comprehensive theoretical and data synthesis analyses. Soliveres et al. (2014)[4] identified the pivotal role of vegetation cover in shaping plant diversity and ecosystem multifunctionality across global arid regions. Furthermore, Chen et al. (2020)[5] scrutinized the ramifications of drought on plant species abundance from the perspective of grasslands, thereby enhancing our comprehension of this domain.

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2. Research Method

2.1 Data Acquisition

The data are sourced from the Xilin Gol Grassland Ecosystem National Field Scientific Observation and Research Station in Inner Mongolia, China. Situated at geographical coordinates of 43°38′N, 116 42′E, the Xilingol Grassland Station is located in one of the most representative areas of typical temperate grassland in China. The climate in this region is classified as semi-arid grassland. Dominant communities in this area include Leymus chinensis and Stipa grandis. The region is prone to frequent occurrences of floods and droughts, with 208 and 461 incidents recorded since 1949, respectively, with irregular weather events predominantly happening during summer.

The specific data comprise atmospheric monitoring records from the Xilingol Station in Inner Mongolia spanning from 2005 to 2008, as well as biological monitoring data collected during the same period. The atmospheric monitoring data encompass various parameters such as monthly average temperature (℃), monthly average ground temperature (℃), monthly average atmospheric pressure (ppm), monthly average relative humidity (%), monthly total precipitation (0.1mm), and monthly total evaporation (0.1mm) [6, 7].

Biological monitoring data consist of plant community characteristics, including plant species and community coverage (%), as well as plant community species composition, including plant number and plant coverage (%).

2.2 The Derivation of The Influence Factor Alpha

We have analyzed the trends in the atmospheric environment from 2005 to 2008 (See Figure 1). To better illustrate the disparity between precipitation and evaporation, we introduce a novel concept termed "net precipitation," defined as the difference between precipitation and evaporation. Upon examination of the Figure 1, it becomes evident that variables such as temperature, evaporation, precipitation, and net precipitation exhibit periodic fluctuations. Notably, net precipitation demonstrates substantial annual variations, indicating its significance in both data preprocessing and research analysis.

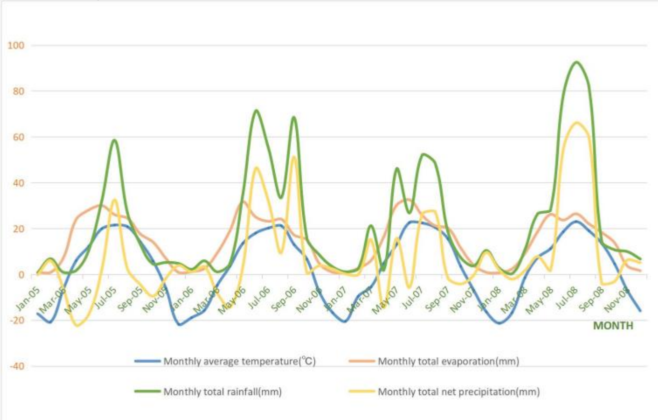
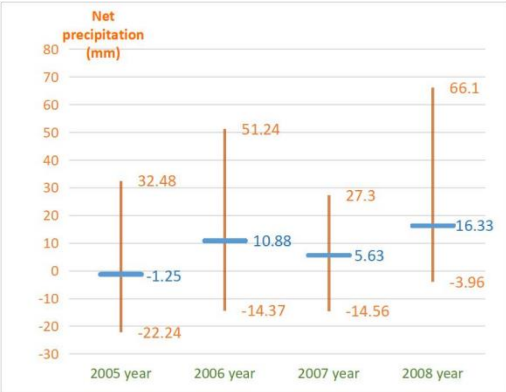


Figure 1 Relationship between atmospheric data and species number

The analysis of net precipitation data reveals significant year-to-year variations(See Figure 2,3). In certain months, the net precipitation substantially deviates from the average value for the corresponding period, suggesting the potential occurrence of floods or droughts based on these irregular weather patterns. For instance, the average annual net precipitation and total precipitation for several months in 2005 were notably lower than the period's average, indicating the presence of one or more droughts during that year.



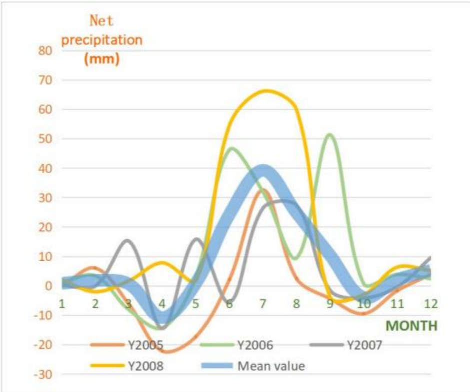


Figure 2 (Left) Maximum, minimum and average of net precipitation

Figure 3 (Right) Change of net precipitation in different years

Continuing the analysis of monthly net precipitation from 2005 to 2008, we proceed with the normalization process to calculate the impact of irregular weather during this period. Firstly, we calculate the average net precipitation for each month over the four-year period. Secondly, we determine the impact weight of each month by dividing the absolute value of the mean monthly net precipitation by the mean annual net precipitation. Thirdly, we normalize the monthly net precipitation using Formula 1.

$$NVMNP = \frac{(NPM - MVSP)}{|MVSP| \times MIW} \tag{1}$$

The meaning of each symbol is shown in the Table 1 below.

Table 1 The meanings of each symbol

Symbol	Meaning
NVMNP	Normalized Value of Monthly Net Precipitation
NPM	Net Precipitation of the Month
MVSP	Mean Value of the Same Period
MIW	Monthly Impact Weight

This process allows us to quantify and compare the influence of irregular weather across different months, providing valuable insights into the variability and severity of weather conditions throughout the study period.

Continuing with the data filtering process, significant drought conditions (represented in orange) are identified when the normalized value of monthly net precipitation is below -0.1(See Figure 4). Conversely, significant flood events (depicted in blue) are determined when the normalized value of monthly net precipitation exceeds 0.1. This categorization facilitates the identification and visualization of extreme weather events, aiding in the analysis of their occurrence and impacts over the study period.

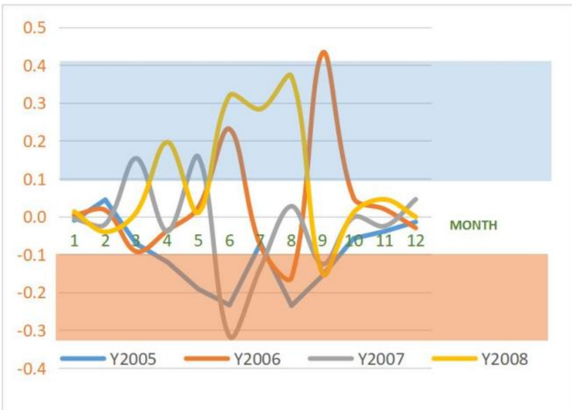


Figure 4 Change of normalized value in different years

The conversion of standardized values into the influence alpha is depicted in Table 2.

Table 2 Conversion of normalized values to influence degrees for drought and flood impacts

Impact Type	Normalized Value Range	Influence Degree Range
Drought	(minimum, -0.1)	(-0.5, -1.5)
Flood	(0.1, maximum)	(-0.5, -1.5)

3. The Establishment of Model

Firstly, let's define f(t) as the number of plants in month t. The f(t) function can be divided into three components: the original number of plants, the natural growth number, and the accidental death number.

In this paper, given the calculation interval of one month, the original data represents the number of plants in the previous month, denoted as f(t-1). For the natural growth component, we utilize the logistic function to depict the S-shaped natural growth curve. Under normal conditions, the plant population increases according to this function. The expression of the logistic function is as follows:

$$P(t) = \frac{KP_0 e^{rt}}{K + P_0(e^{rt} - 1)} \tag{2}$$

Where r represents the natural growth rate, P denotes the current plant quantity, t signifies the time, and K represents the maximum environmental capacity of the plant community. Consequently, the rate of change per unit time of the logistic function corresponds to the increase in plant quantity.

In this paper, f (t-1) represents the current plant quantity, specifically referring to the number of plants in the previous month.

$$P = f(t-1) \tag{3}$$

$$\frac{\mathrm{d}P}{\mathrm{dt}} = rf(t-1)(1 - \frac{f(t-1)}{K}) \tag{4}$$

The number of accidental deaths comprises two components.

Firstly, there is the severity of the disaster, denoted by α. α represents the impact degree of natural disasters such as drought and flood, and it follows a normal distribution with a mean of -1 and a variance of 0.0625. α indicates the extent of influence exerted by the disasters. Secondly, there is the impact range of the interaction between plant communities due to the reduction of natural disasters, which ranges from 0 to 1.

According to article[1], when there are only 1-2 species, the damage rate of disasters reaches 50%, while when the number of species reaches 32-64, the damage rate of disasters is generally 25%. Therefore, function I represents the relationship between the number of species and the ability of plant communities to resist disasters, and S represents the number of species.

$$I = 0.75 * (1 - \frac{\log_2 s}{9}) \tag{5}$$

Therefore, the accidental death rate in month t is:

$$0.75\alpha(1 - \frac{\log_2 s}{9}) * f(t-1) \tag{6}$$

It is assumed that when a disaster occurs, it will not grow naturally in that month, and there will be at most one disaster in each month. Because the disaster occurs randomly, p is the frequency of the previous disaster in the region, so Poisson distribution is used to calculate the probability g of the random disaster.The Poisson distribution formula is as follows:

$$P(X=k)=\frac{\lambda^k}{k!}e^{-\lambda},\quad k=0,1,\cdots \tag{7}$$

where e is the base of the natural logarithm, λis the average number of events in a given time interval, k is the number of events that occur in that interval, and k! denotes the factorial of k.

Because disasters occur only once a month at most, the Poisson distribution can be employed to obtain:

$$g=pe^{-p} \tag{8}$$

G is a random function. It outputs a probability of 1 (indicating a disaster in the current month) with a probability g, and it outputs a probability of 0 (indicating no disaster in the current month) with a probability of 1−g.

Therefore, the plant quantity prediction model is as follows:

$$\begin{cases} f(t)=f(t-1)+G*\alpha*I*f(t-1)+(1-G)*\dfrac{\mathrm{d}P}{\mathrm{d}t} \\ g=pe^{-p} \\ I=0.75*(1-\dfrac{\log_2 s}{9}) \\ \dfrac{\mathrm{d}P}{\mathrm{d}t}=rf(t-1)(1-\dfrac{f(t-1)}{K}) \end{cases}$$

4. Validation of Model

Since the observation station only recorded the number of plant species from May to October each year, we will use the number of plant species from May 2005 as the initial value to predict the change of plant species in this area from May 2005 to October 2008. We will incorporate the impact degree of drought and flood obtained from the data preprocessing into the model at each timestep during this period. Subsequently, we will generate a comparison diagram between the actual values and the simulated values(See Figure 5).

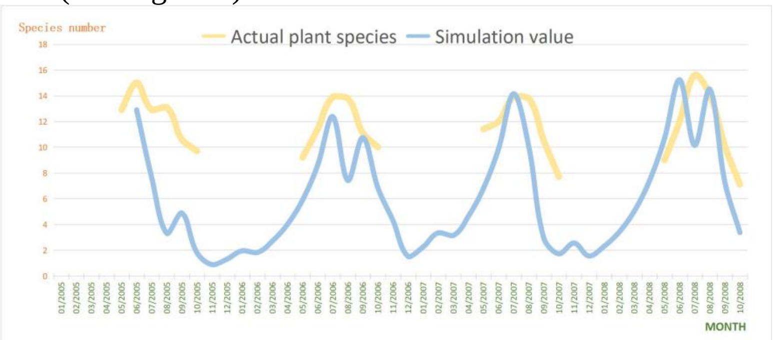


Figure 5 Relationship between actual plant species and simulation value

Intuitively, the trend of the simulated values closely matches the actual values, with both showing similar patterns over time. Additionally, the magnitudes of the simulated values closely align with those of the actual values, indicating a high level of agreement between the model predictions and the observed data.

Pearson correlation analysis can be utilized to assess the correlation between the simulated values and the actual values. We incorporate the data of simulated values and actual values into Pearson's correlation coefficient calculation formula (Formula 9):

$$\frac{N\sum x_i y_i-\sum x_i\sum y_i}{\sqrt{N\sum x_i^2-(\sum x_i)^2}\sqrt{N\sum y_i^2-(\sum y_i)^2}} \tag{9}$$

The Pearson correlation coefficient is 0.629. With a correlation coefficient falling within the range of 0.6-0.8, it indicates a strong correlation.

Hence, we can conclude that there is a strong correlation between the observed plant species number and the model-predicted values.

5. Sensitivity Analysis

To illustrate the sensitivity of the prediction model, three representative parameters are selected as the focus of analysis.

a) Number of plant species f (t-1)

b) Impact degree α

c) Maximum natural growth rate r

Make these three parameters increase by 10%, 15%, 20%, 25% and 30% respectively from the initial value of 500, -0.88 and 0.5. After a period of prediction, fill the predicted number of plant species in table 3.

Table 3 Change of the parameters

Change	Number of plant species f (t-1)	Impact degree α	Maximum natural growth rate r
10%	521.62	480.65	463.34
15%	544.66	472.27	468.95
20%	567.34	463.83	474.56
25%	589.64	455.33	480.17
30%	611.57	446.77	485.78

According to the table 3, calculate the rate of change and get table 4.

Table 4 Correlation coefficient

Change	Number of plant species f (t-1)	Impact degree α	Maximum natural growth rate r
10%	0.1	0.03	0.025
15%	0.15	0.05	0.037
20%	0.19	0.07	0.05
25%	0.24	0.084	0.06
30%	0.29	0.12	0.074

To visualize the above data:

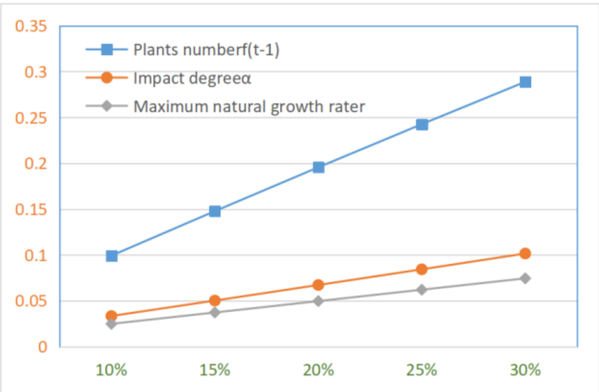


Figure 6 Correlation coefficient visualization

The analysis of the figure 6 reveals that the sensitivity of the number of plant species f(t−1) is the highest. When the number of plant species changes, it has the greatest impact on the community, surpassing the influence of irregular weather on the community. Consequently, increasing the diversity of plant species in the community can effectively mitigate the impact of irregular weather, aligning with the objectives of the study and the purpose of the prediction model.

6. Results and Conclusion

6.1 Results

To obtain the number of plant species that can benefit the community, we employ the control variable method. This involves creating communities with different initial species but placing them in the same environmental conditions. This ensures that these communities will experience the same frequency and degree of impact from irregular weather over a specified period of time. We continue to use the Poisson distribution to determine the frequency and the normal distribution to determine the influence degree of a set of irregular weather events, serving as the control environmental variables.

To predict the change in species number within one year and assess the community recovery ability, we will utilize the controlled environment variables provided. The occurrence sequence of irregular weather events (G) and their corresponding impact degrees (α) will be incorporated into the predictions.

The values of G and α are as follows:

G =(1,1,0,1,0,1,0,0,0,0,0,0);

α =(-1.17, -1.16, -1.19, -1.09, -1.29, -0.62, -1.09, -0.8, -1.07, -1.03, -0.94, -0.53).

We will bring in different initial plant species values (S) and observe how the species number changes over one year. If the number of plant species returns to the initial value after one year, we will consider the initial number of plant species as beneficial to the community.

The values of S are as follows:

S =(1, 2, 4, 8, 10, 12, 14, 16, 32, 64).

Based on the results, we will evaluate the community recovery ability and survival rate. If S=12 remains close to the initial value of 12 after one year, it indicates a strong community recovery ability(See Figure 7).

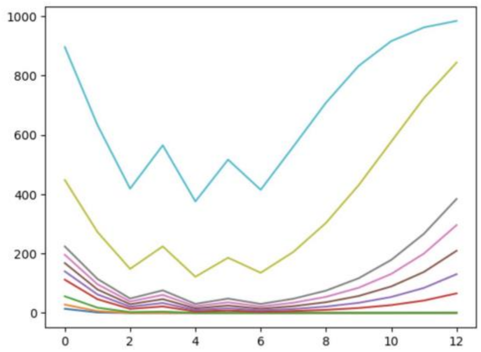


Figure 7 Changes of different number of plants in the same environment

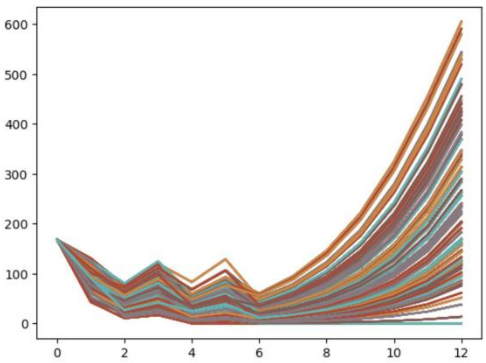


Figure 8 Simulate 100 times

We further analyzed the community with an initial number of 12 species under different environmental conditions, and the results are shown in the Figure 8 below. Statistical analysis shows that there is more than 70% probability that the number of plant species in the community will return to its initial value after one year. This finding is consistent with the average natural mortality rate for plants in nature of approximately 30%. Therefore, it is reasonable for a community with 12 plant species to have a survival rate of 70% in nature.

The change in plant species observed in the biological monitoring data of Inner Mongolia closely aligns with the predicted result of a community with 12 species. Over the period from 2005 to 2008, the average number of plant species recorded was 11.7, which is remarkably close to the calculated result of 12(See Figure 9). This consistency indicates that the actual number of plant species indeed tends towards 12.

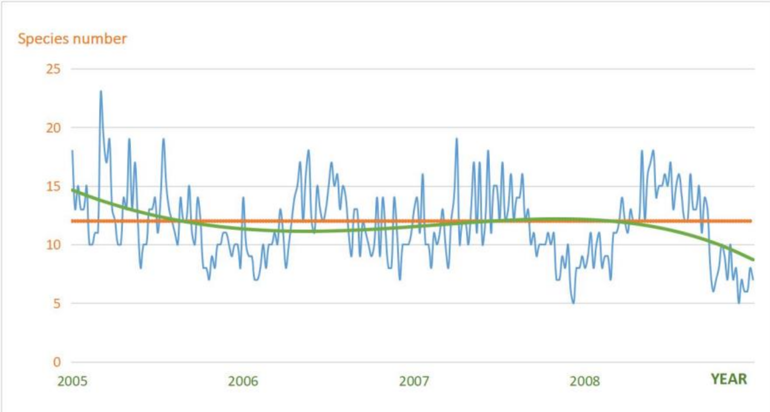


Figure 9 The relationship between population number in Inner Mongolia and 12

Using the same methodology, we computed the survival rate curve of the community under varying species numbers. The results indicate that as the number of species increases, the survival rate also rises. However, as the number of species continues to increase, the rate of increase in the survival rate gradually diminishes(See Figure 10).

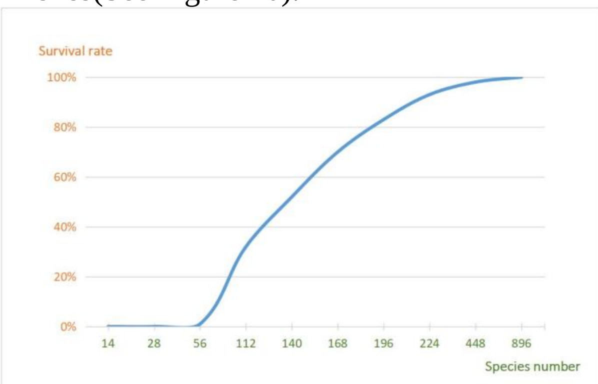


Figure 10 Relationship between survival rate and species number

6.2 Conclusion

Our research shows that: increasing community plant species diversity can effectively weaken the impact of irregular weather; a community composed of 12 plant species is beneficial; increasing the number of species can enhance the vitality of the community, but as the number of species continues to increase, survival The rate at which abilities increase will be reduced.

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