A study of plant community diversity based on quantitative analysis model and prediction model

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Abstract. Plant community species diversity is the pivot that connects ecosystem multi functionality and environmental change. In order to explore the influence of community species number on drought adaptation, this paper uses logistic fitting and residual verification formed by grayscale accumulation to obtain the population dynamics change curve under ideal conditions, followed by selecting indicators such as soil moisture amount and plant growth rate, and establishing a prediction model based on the plant growth pattern of plant communities under different weather cycles and the interaction mechanism between different species, and The conclusions were drawn, which provided a theoretical basis of the subsequent research on the population size under drought conditions.

Keywords: Logistic Fitting, Interspecific Relationship Mechanisms, Predictive Models.

1. Introduction

Different species of plants respond to stress in different ways, and the problem of drought is one of the very important aspects. In order to explore the relationship between the number of species and the role of plant communities due to drought, the relationship between drought adaptation and the number in plant communities is considered [1-2]. In this paper, a predictive model was established by means of mathematical modeling, considering the population size under non-environmental factors, plant growth patterns [3], and the interaction mechanism between different species to derive the change of plant communities over time for various irregular weather cycles.

In this paper, a quantitative analysis model of population dynamics under ideal conditions was established by discretizing and fitting the data based on the net growth data onto the number of individuals in the population under the influence of non-environmental factors. On this basis, the species change functions and prediction curves over time were obtained by selecting suitable indicators to establish and combining the mechanisms of inter-population interactions, and finally, the evaluation and outlook of the model were carried out.

2. Model building and solving

2.1. A population dynamics model based on quantitative analysis

2.1.1 Data Collection

The problem does not directly give the relevant data to build the model. Data we need including world climate, plant and animal diversity, and plant and animal biomass are used throughout the text and are taken from the following table at Table 1:

Table.1. Data source collation

Database Names	Database Websites Data
World Climate	https://www.worldclim.org/data/index.htm
Biodiversity	https://www.gbif.org/
Marine Biodiversity	https://obis.org/
Global Disaster Database	http://learning.richmond.edu/disaster/index.cfm

2.1.2 Data description

From the papers of Ju-Rong Tan, Wei-Gao Yuan, and Ting-Ting Li, combined with relevant online data, we selected the Tibetan Plateau, a representative plant community, and obtained data on the net increase in the number of individuals in the population for 60 years under the influence of non-environmental factors. (Five populations (herbs represented by mint, shrubs represented by rose, semi-shrubs represented by Astragalus, lianas represented by moon, and trees represented by birch))[4].

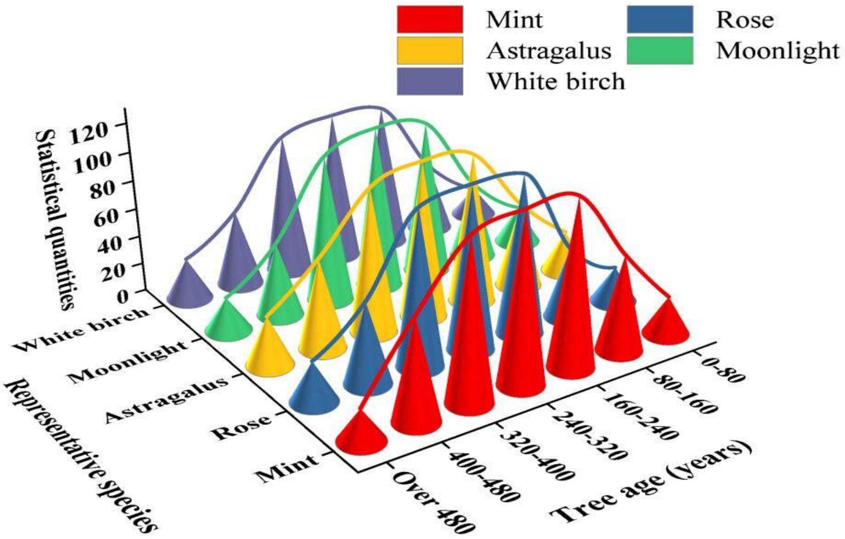

Figure 1. Statistical results by age for different categories of trees on the Tibetan plateau

From the statistical results in Figure 1 above, it is easy to see: the curve of the number of different categories of vegetation roughly increases first and then decreases.

2.1.3 Data discretization and cumulative fitting

We discretize the obtained curve data by selecting a data point ($\Delta N_i^{(0)}(k)$) every 10 years, which constitutes a set of time series data, and then, we perform accumulation to generate time series data of the total number of individuals in the population [5]:

$$\{\Delta N_i^{(0)}(1), \Delta N_i^{(0)}(2), \ldots, \Delta N_i^{(0)}(n)\} \xrightarrow{N_i^{(1)}(k)=\sum_{p=1}^{k}\Delta N_i^{(0)}(p)}$$

$$\{N_i^{(1)}(1), N_i^{(1)}(2), \ldots, N_i^{(1)}(n)\} = N_i, n = 1, 2, \ldots, 7, i = 1, 2, 3, \ldots, 5$$

By observing the change trend of the data set N_i, we can see that the number of individuals in the population changes over time in a roughly "S"-shaped growth process, and the logistic function itself is to describe the growth law of the population under the condition of limited resources and the same "S"-shaped growth [6], so we can borrow the function to fit to obtain.

$$\frac{dX}{dt} = r \times X \times (1 - \frac{X}{K}) \longrightarrow X(t) = \frac{KX_0 e^{rt}}{K + X_0(e^{rt} - 1)} \tag{1}$$

Where K represents the final number of individuals in the population, X_0 is the initial number of individuals in the population, and r indicates the growth rate of the number of individuals in the population.

Fitting and calculating the function parameters, the final fitted curves for the number of individuals in the five different populations over time can be obtained, as shown in figure 2 below.

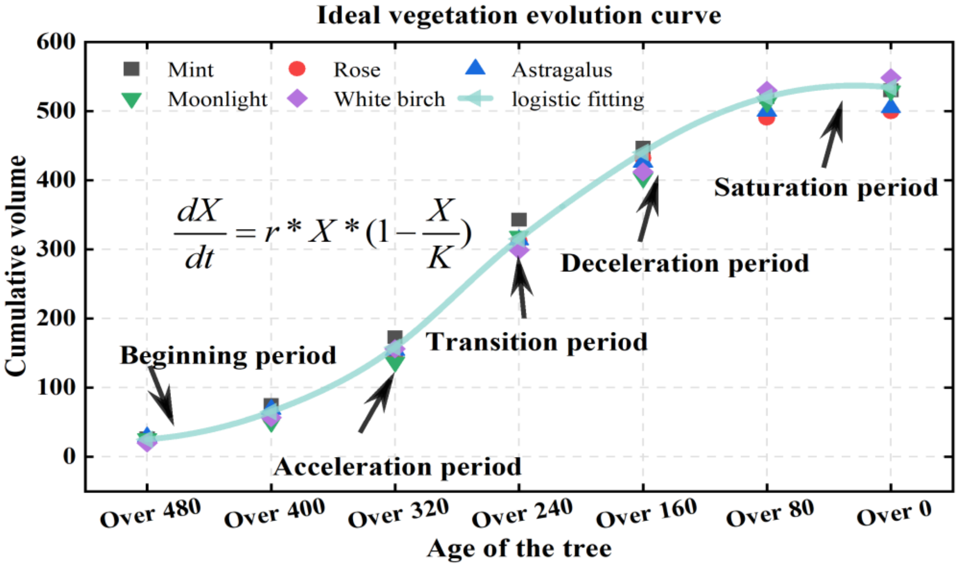

Figure 2. Logistic fitting curve results

The following table shows the calculated values of the residuals between the cumulative number of individuals in the population at each stage and the predicted values, which are calculated as: $(\bar{y}-y)^2$.

Table.2. Residual test results

Statistical quantities	Over 480	Over 400	Over 320	Over 240	Over 160	Over 80	Over 0
Residual values	1.1	3.5	13.9	28.9	35.6	29.1	27.9
y_{mean}	15.4	63.7	157.8	312.9	443.2	512.4	520.4

It can be seen from Table 2 that the residual data is much smaller than the average of the data to be fitted at each stage, that is:

$$\text{Re}\,sidual\ values \le 0.01 y_{mean} \tag{2}$$

Therefore, our proposed logistic fitting function passed the residual verification and obtained a good fitting result.

In the next section we consider the mechanism of interaction of environmental factors such as drought on different species in the community, and predict the trend of the community over time.

2.2. Predictive model based on biological evolutionary mechanism

2.2.1 Relative moisture content index

The direct source of water required for plant growth is water in the soil, from which plants draw water, organic matter and other nutrients for growth. Therefore, we introduced soil moisture indicators to quantify the changes in the degree of environmental aridity.

$$W_t = W_{t-1} + P + W_k + W_r - E_0 \tag{3}$$

Where W_t denotes the soil water content of the planned wet layer at time t, P expresses the amount of precipitation in the period $t-1$ to t, W_t is the amount of groundwater use in the time period $t-1$ to t, W_t represents the increase in water volume due to the deepening of the planned wetted layer from time period $t-1$ to t, E_0 is the plant water demand from time $t-1$ to t. On this basis, we can further express the relative water content of the soil from time $t-1$ to t:

$$\Delta W = \frac{W_t - W_{t-1}}{W_{t-1}} = \frac{P + W_k + W_r - E_0}{W_{t-1}} \tag{4}$$

In the next section, we first introduce the effect of environmental factors such as drought on plant growth rate.

2.2.2 Plant growth rate index

For plant growth, photosynthesis is the main pathway of biomass accumulation, while plant respiration, stem and leaf abscission, and root death decomposition are the processes of biomass depletion, and the combination of these processes results in the growing season dynamics of vegetation biomass [7-8]. In water-limited ecosystems, soil moisture is the main factor affecting the photosynthetic rate and transpiration rate of plants. And plant growth rate can be expressed by the net increase in plant biomass per unit time. Therefore, we established the equation that soil moisture affects plant growth rate by influencing plant photosynthetic rate and transpiration rate. The specific procedure is as follows.

First, the hypothesis is given that leaf stomata are fully open when $\Delta W \geq \Delta W_s$ (ΔW_s is the relative soil water content at the time of plant wilting) and closed when $\Delta W < \Delta W_s$.

At full opening of plant leaf stomata, we can obtain the following equation after introducing the plant functional trait parameters and soil hydraulic parameters.

$$r = \frac{dH}{dt} = H[Sf_e Y_g (\frac{A_m[\Delta W - \Delta W_s]}{k + [\Delta W - \Delta W_s]}) - (1 - f_e)R_r - q] \tag{5}$$

Among them,

$$nE_r \frac{d\Delta W}{dt} = P - HSf_e Y_g (\frac{E_m[\Delta W - \Delta W_s]}{k + [\Delta W - \Delta W_s]}) - K_s C^s \tag{6}$$

Where H indicates the biomass contained in the plant, S represents the specific leaf area, Y_g is the assimilation efficiency, f_e expresses the leaf dry matter content, A_m and E_m are the daily potential assimilation and daily potential evapotranspiration, respectively, k represents the half-saturation coefficient(The value of $\Delta W - \Delta W_s$ when E_D is half of E_m), n is the soil porosity, R_r indicates the root respiration coefficient, $K_s C^s$ for deep seepage(K_s represents the saturated hydraulic conductivity of the soil and S represents a constant with respect to soil type), q expresses the rate of mechanical attrition (stem and leaf loss, fine root death, etc.)

Next, we set:

$$\lambda = \frac{Sf_e Y_g E_m}{nE_r}, \eta = A_m Sf_e Y_g, \varepsilon = R_r(1 - f_e) + q \tag{7}$$

We found that these three parameters have exactly their practical significance: λ represents the maximum transpiration rate per unit biomass, η represents the maximum assimilation rate, that is, the relative growth rate, and ε represents the rate of loss caused by root respiration, death and shedding of fine roots and leaves.

Simplifying the equation yields the final function as:

$$r = \frac{dH}{dt} = H[(\frac{\eta[\Delta W - \Delta W_s]}{k + [\Delta W - \Delta W_s]}) - \varepsilon] \tag{8}$$

$$\frac{d\Delta W}{dt} = \frac{P}{nE_r} - H(\frac{\lambda[\Delta W - \Delta W_s]}{k + [\Delta W - \Delta W_s]}) - K_s C^s \tag{9}$$

In the case of plant stomatal closure, we can classify as a special case of the above final function, that is: $\lambda = \eta = 0$. It can simplify to:

$$r=\frac{dH}{dt}=-\varepsilon H \tag{10}$$

$$\frac{d\Delta W}{dt}=\frac{P}{nE_r}-K_sC^s \tag{11}$$

Use this figure 3 below to illustrate the following:

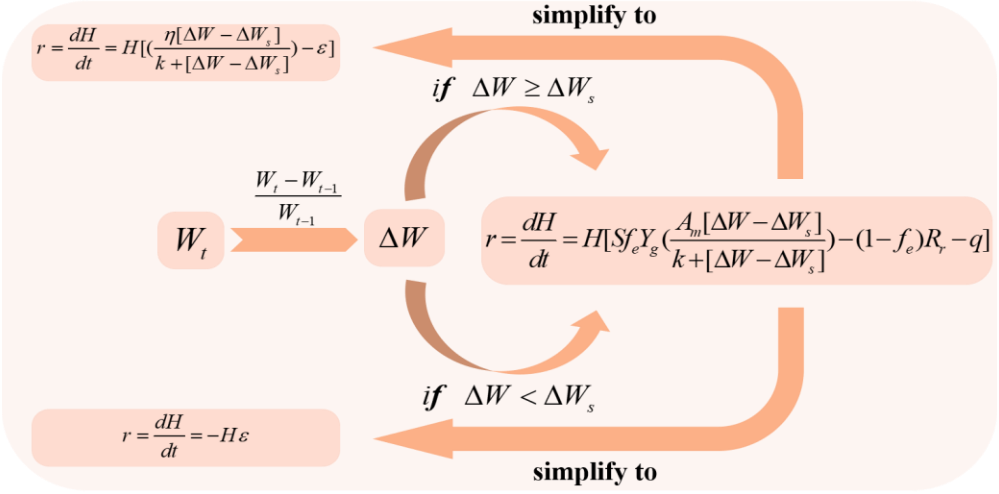

Figure 3. Introduction to the formula

In the next section, we define the mechanisms of interaction between different species under drought stress. Since different species have different growth rates and respond differently to drought cycle stress, we model below the interaction mechanisms between other species in the plant community and this species for a particular species.

2.2.3 Mechanisms of interspecific relationships under drought cycle stress

When there are different populations in a community, under limited environmental resources, there will be competition between populations regardless of whether they are under drought stress or not. Therefore, we first modeled the population competition under non-drought stress as:

$$\frac{dX}{dt}=rX\,(1-\frac{X}{n_1}-S_1\frac{X_2}{n_2}-S_2\frac{X_3}{n_3}-\ldots-S_{n-1}\frac{X_n}{n_n}) \tag{12}$$

Where $X_2, X_3, X_4, \ldots, X_n$ represent the number of individuals of other species in the plant community that are distinct from the unknown species, $n_1, n_2, \ldots, n_n$ indicates the maximum holding capacity of different species in the community(n_1 is the maximum holding capacity of species X), $S_1, S_2, \ldots, S_{n-1}$ express the number of resources in the community consumed by the species corresponding to $X_2, X_3, X_4, \ldots, X_n$ relative to the unknown species, respectively.

We reviewed a large amount of literature and found that under long-term water stress, plants increase nutrient concentrations and enhance community resistance through endostasis mechanisms, and species turnover is the main influence of this process [9-11]. So, we believe that the main interaction mechanism of different species in the community under drought stress is the process by which they compete with each other for resources.

Therefore, we believe that the main interaction mechanism of different species in the community under drought stress is the process by which they compete for resources in a reciprocal manner. For equation (11), the main effect is on the $S_1, S_2, \ldots, S_{n-1}$. In the drought cycle, we assume that the variation of $S_1, S_2, \ldots, S_{n-1}$ follows the following functional relationship:

$$S_i = Rate\sin(\frac{2\pi\vartheta}{T}X_{i+1}), i = 1,2,...,n-1 \tag{13}$$

Where T represents a drought cycle and $Rate$, ϑ are regulators to achieve the degree of variation in resource consumption of different species relative to the unknown species.

2.2.4 Prediction curves for different species populations

Changes in the abundance of a species in a plant community are not only related to intra-species competition, but also to competition among other species. When the climatic environment changes, the growth of the species itself will change, and other species will also respond to the environment and affect the change in the population of the species [12]. Combining equations (1), (9)-(12) in sections 2.1.3, 2.2.2 and 2.2.3, we can obtain the population change function of a species in the community over time. The specific procedure is as follows.

The differential equation (11) is first solved: to make the calculation easy, we integrate the non-time variables so that $Z = 1 - S_1\frac{X_2}{n_2} - S_2\frac{X_3}{n_3} - ... - S_{n-1}\frac{X_n}{n_n}$, and the original equation can be reduced to:

$$\frac{dX}{dt} = rZX - \frac{rX^2}{n_1} \longrightarrow \frac{1}{Zn_1}(\frac{1}{X} + \frac{r}{Zn_1 - rX})dX = dt \longrightarrow X = \frac{1+re^{Zn_1t}}{Zn_1re^{Zn_1t}} \tag{14}$$

Next, we can obtain the number of individuals of the final species as a function of time:

$$X(t) = \frac{KX_0e^{rt}}{K + X_0(e^{rt}-1)} + \frac{1+re^{Zn_1t}}{Zn_1re^{Zn_1t}} + \varpi \tag{15}$$

Where ϖ represents a disturbance term to represent the effect of other factors such as environmental pollution and habitat reduction on the change in the number of individuals of the species.

To better express the range and trend of species population change, we improved the function dependent variable as follows:

$$Y(t) = \frac{X(t)}{\sum_{i=1}^{t} X(i)} \times 100\% \tag{16}$$

In this way we can clearly see the pattern of species change over time by simply looking at the percentage change in the number of species at each moment.

The community was then simulated for different weather conditions ($\varpi = 0$) using equation (14) to calculate the change in the number of individuals of each species in the community over time under four different climatic conditions, with the following curves:

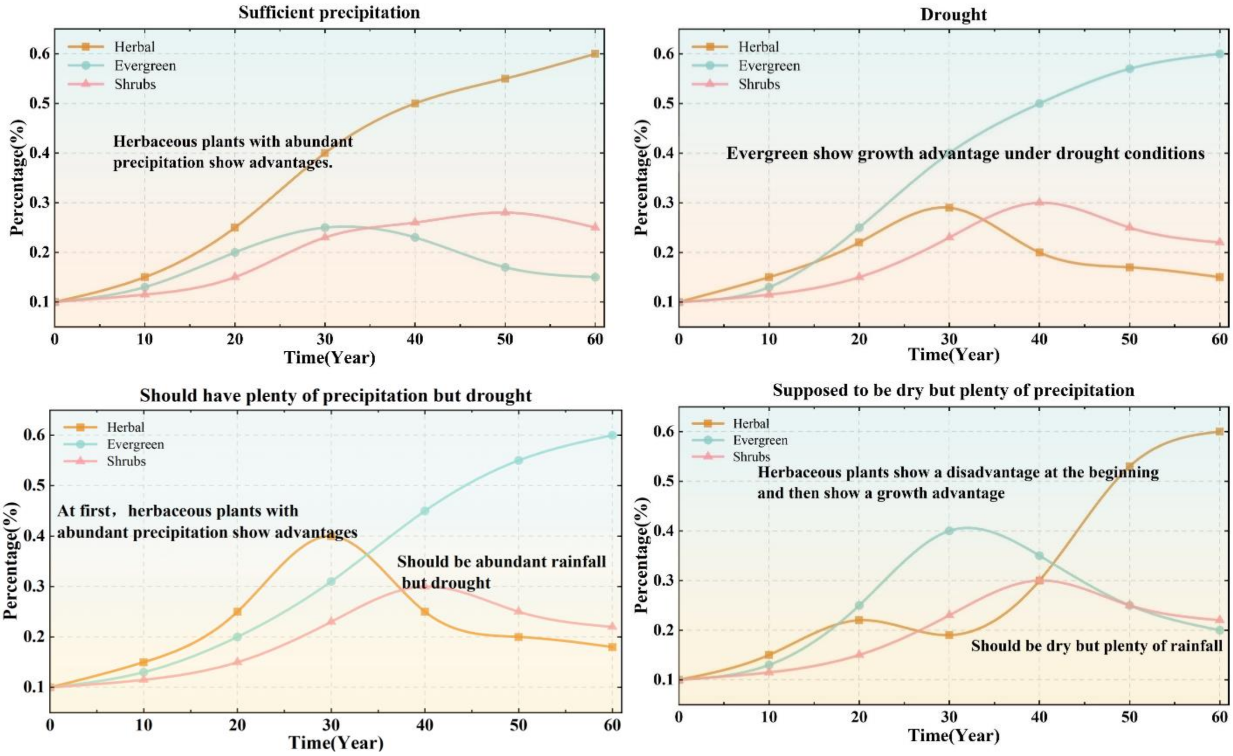

Figure 4. Curves of species population change under different climatic conditions (When $\varpi = 0$)

The Figure 4 shows that for herbaceous plants, which have the highest water demand, they are more affected by droughts when they should be wet; the maximum percentage of their species decreases from 60.3% to 39.7% of all species. For shrubs, there was little variation in response to different weather conditions; for trees, the least water-demanding species, they were more affected by weather that should have been dry but had sufficient precipitation. The main reason for this was the growth advantage of herbaceous plants that absorbed large amounts of water.

3. Conclusions

The advantages of the model are:

(1) The base model is accurate: We collect a large amount of data, analyze and compare it to select relatively accurate data, simulate it to get the base model, and pass various statistical tests to get the prediction with reliability.

(2) Implementation of the exact results: The population categories for which the best adaptations were obtained in this paper were about four species, which did not differ much from the results of other scholars' studies.

The limitations of the model are:

Since the data set selected for the base model is limited, if we have more data, we can simulate the vegetation growth model using different functions and take the weighted average of the simulation results of each function, we may get more accurate results and more factors will be considered in the model.

4. Model Evaluation

Plant community species diversity is the pivot that connects ecosystem multi functionality and environmental change. In this paper, we have established a quantitative analysis model of population dynamics and a prediction model based on biological evolutionary mechanism, and studied the mechanism of interspecific relationships. The final results showed that species with high water demand were more affected in the case of abundant precipitation but dry weather, and their maximum proportion of the total population decreased in 60.3% to 39.7%.

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