A Dynamical System on How Plant Communities are Affected by Environment Factors and Population interactions

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Abstract. The plant community has natural adaptability and resistance to the habitat environment. However, when the climate conditions of the habitat change, the growth status of the plant Community will also change. Intraspecific and interspecific competition also affect plant growth in the face of climate change. This paper will try to illustrate how plant communities are affected by environmental factors over time, where precipitation is the main element taken into consideration. First, build a model to analyze and predict the relationship between drought adaptation and the number of species in a plant community. Second, modeling the effects of mutual cooperation and competition between populations and incorporating effects on drought adaptation. Third, based on the model, predict the minimum number of species required for a plant community to benefit from local biodiversity. Finally, we discuss the effects of increased frequency and severity of drought on plant communities and make recommendations for the optimization of biodiversity.

Keywords: dynamical system; plant community; precipitation; interspecies relationship.

1. Introduction

A plant community is a combination of reciprocal and competitive interactions of all plants living in a certain area and the result of the adaptation to their living environment. The number of plant species contained in a plant community is essential for its adaptability to the environment, while the environment also has an impact on the composition of the community.

As a major contributor to changes in plant diversity and biomass in arid and semi-arid regions, water affects the growth and species composition of plants, and is a crucial factor in determining community productivity and species diversity. In areas where water is relatively scarce, finding the species composition of plant communities that are best adapted to the environment becomes a viable option for optimizing biodiversity and ecology.

2. Establishment of the Model

2.1. Objective Function

To model the relationship between species change and climate environment and population interactions, we solve for changes in plant populations using a differential equation:

$$\frac{\mathrm{dx_{i(t+1)}}}{dt} = r_i(t) \cdot x_i(t) \tag{1}$$

Where $\frac{\mathrm{dx_{i(t+1)}}}{\mathrm{dt}}$ represents the change in the population of species i at period t+1, which is determined by the species at the previous time. Plant growth rate is mainly affected by environmental factors and its own population relationships.

$$r_i(t) = r_{ei}(t) + r_{bi}(t) \tag{2}$$

2.2. Environment Constraints

In correlation analysis, precipitation can replace soil moisture as an index to quantify the effect of climate on plants, based on which, we established the relationship between rainfall and plant growth

rate under the influence of environmental factors. Since the growth rate of plants in the natural state gradually increases with the increase of rainfall and finally flattens out, the following relationship is established:

$$r_{ei}(t) = \frac{L_i}{1+e^{-\omega h(t)}} - \frac{L_i}{1+e^{-wh_{mean}}} \tag{3}$$

Where L_i is the maximum growth rate of species i, ω is the parameter, h is the precipitation between (0,1) after normalization.

2.3. Plant interactions Constraints

Plants in natural systems live symbiotic lives, but they are not independent of each other, and there is a general interaction between them. Plant positive and negative interactions often exist and function simultaneously in natural ecosystems. Positive plant interaction is defined as an interaction within or between plants that promotes the survival, growth or reproduction of adjacent individuals and is beneficial to at least one of the adjacent individuals but not to the other. Negative plant interaction refers to the dynamics in which the growth rates, survival rates and reproduction rates of individual plants decrease due to the sharing of locally restricted resources. Interactions between plants include positive interactions (promotion) and negative interactions (competition). The relationship between plant interaction and plant growth rate is expressed as follows:

$$r_{bi}(t) = r_{bip}(t) - r_{bin}(t) \tag{4}$$

$$r_{bip}(t) = \alpha \sum_{k=1}^{n} \left(\frac{x_{k(t)}}{\sum_{j=1}^{n} x_{j(t)}} \right)^{ln(n+1)\cdot\mu_{ki}} \tag{5}$$

$$r_{bin}(t) = \beta \sum_{k=1}^{n} \left(\frac{x_{k(t)}}{\sum_{j=1}^{n} x_{j(t)}} \right)^{ln(n+1)\cdot\lambda_{ki}} \tag{6}$$

Where $\alpha = 1/(1 + e^{-(h(t)-h_{mean})})$ is a factor of mutual aid,

β is a factor of competition,

μ is the parameter of plant mutual aid respectively between species k and species i,

λ is the parameter of plant competition between species k and species i.

The two matrices below indicate that the cooperation and competition coefficients which obtained from model I are normalized to between 0 and 1. The competition and cooperation between the two species are affected by the nature of the species itself. The coefficient of Interaction of species can be judged according to the root length, root diameter and plant height of the plant. The cooperation index and competition index between the same species are denoted as 0. The closer the cooperation index is to 1, the stronger the positive interaction between species, and the farther the competition index is from 0, the stronger the negative interaction between species. Based on the content of the existing papers, we established a competition and cooperation weight relationship of 22 species. But Due to the large number of plant types, only a few typical plant types are selected.

Table.1. The coefficient of cooperation between two species

		Arbor			Bush			Meadow		
		Ulmus pumila	Dry willow	Locust	Tamarix chinensis	Salix cheilophila	Artemisia desertorum	Triglochin palustris	Leymus secalinus	Salsola passerina
Arbor	Ulmus pumila	0	0.25	0.26	0.45	0.46	0.47	0.64	0.65	0.65
	Dry willow	0.25	0	0.27	0.48	0.48	0.49	0.71	0.72	0.72
	Locust	0.26	0.27	0	0.52	0.52	0.52	0.74	0.75	0.76
Bush	Tamarix chinensis	0.45	0.46	0.47	0	0.25	0.26	0.45	0.46	0.47
	Salix cheilophila	0.48	0.48	0.49	0.25	0	0.27	0.48	0.48	0.49
	Artemisia desertorum	0.52	0.52	0.52	0.26	0.27	0	0.52	0.52	0.52
Meadow	Triglochin palustris	0.64	0.65	0.65	0.45	0.46	0.47	0	0.25	0.26
	Leymus secalinus	0.71	0.72	0.72	0.48	0.48	0.49	0.25	0	0.27
	Salsola passerina	0.74	0.75	0.76	0.52	0.52	0.52	0.26	0.27	0

Table.2. The coefficient of competition between two species

		Arbor			Bush			Meadow		
		Ulmus pumila	Dry willow	Locust	Tamarix chinensis	Salix cheilophila	Artemisia desertorum	Triglochin palustris	Leymus secalinus	Salsola passerina
Arbor	Ulmus pumila	0.72	0.76	0.81	0.45	0.46	0.47	0.21	0.25	0.26
	Dry willow	0.72	0.69	0.84	0.48	0.48	0.49	0.25	0.24	0.27
	Locust	0.73	0.74	0.68	0.52	0.52	0.52	0.26	0.27	0.28
Bush	Tamarix chinensis	0.45	0.46	0.47	0.72	0.76	0.81	0.45	0.46	0.47
	Salix cheilophila	0.48	0.48	0.49	0.72	0.69	0.84	0.48	0.48	0.49
	Artemisia desertorum	0.52	0.52	0.52	0.73	0.74	0.68	0.52	0.52	0.52
Meadow	Triglochin palustris	0.21	0.25	0.26	0.45	0.46	0.47	0.72	0.76	0.81
	Leymus secalinus	0.25	0.24	0.27	0.48	0.48	0.49	0.72	0.69	0.84
	Salsola passerina	0.26	0.27	0.28	0.52	0.52	0.52	0.73	0.74	0.68

2.4. Testing in three real cases in Australia

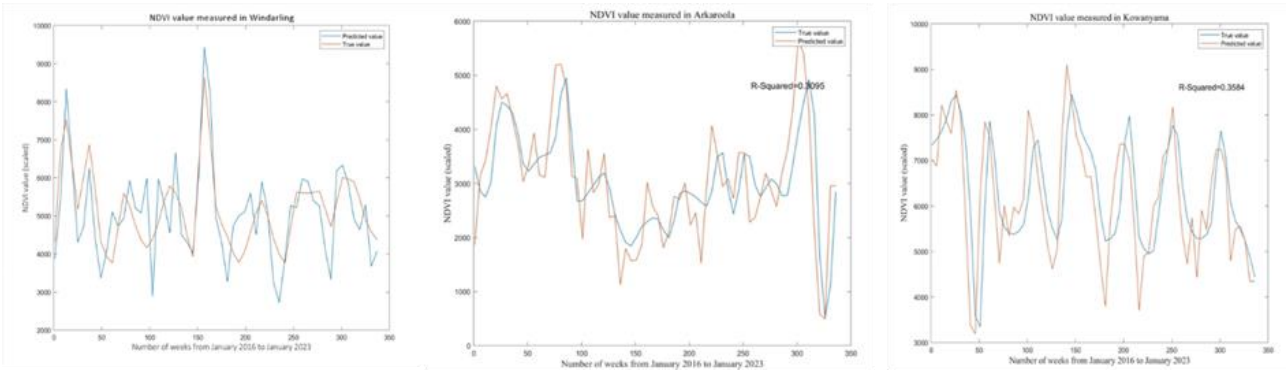


Figure 1. Comparison of NDVI fitting values and true values for three regions

Figure 1 is the comparison between the real value changes of NDVI in three regions over time and our model. Although the variance of in the model fitting result is small, our model reflects the correct trend. Secondly, we found that the peaks and troughs of the true values lagged behind those of the fitting values, because the sensitivity of vegetation water content to soil temperature change and the time lag were not taken into consideration.

3. Optimization model based on leapfrog algorithm

3.1. The Improved Shuffled Frog Leaping Algorithm（ISFLA）

The essence of the optimization model is to search the number of species and the selection combination of plant types under the constraint of number of species heuristically, find the minimum value of volatility, and then get the number of species and plant combination strategy when the volatility is optimal. In the natural case, many kinds of species are selectable, and the search space of combination strategy is also huge. So, the traditional nonlinear optimization method is difficult to get the convergence solution. Therefore, we use the improved Shuffled Frog Leaping Algorithm (ISFLA) to solve this optimization problem. In this paper, we used an improved version named ISFLA. The algorithm introduces chaotic method via creating adaptive perturbation values to guide the algorithm to converge in the global, constructing the "local fine search" and "global incentive adjustment" optimization mechanism. The method coordinates the local exploration ability and global search ability of the algorithm, effectively improves the feasibility and effectiveness of the algorithm.

SFLA is a well-known swarm intelligence optimization algorithm in the field of computational intelligence. ISFLA is an improvement of SFIA via adding an adaptive bias value to the fitness function. Due to the limitation of paper length, we show the general principle of the algorithm and related terms that may be used in the following table and flowchart.

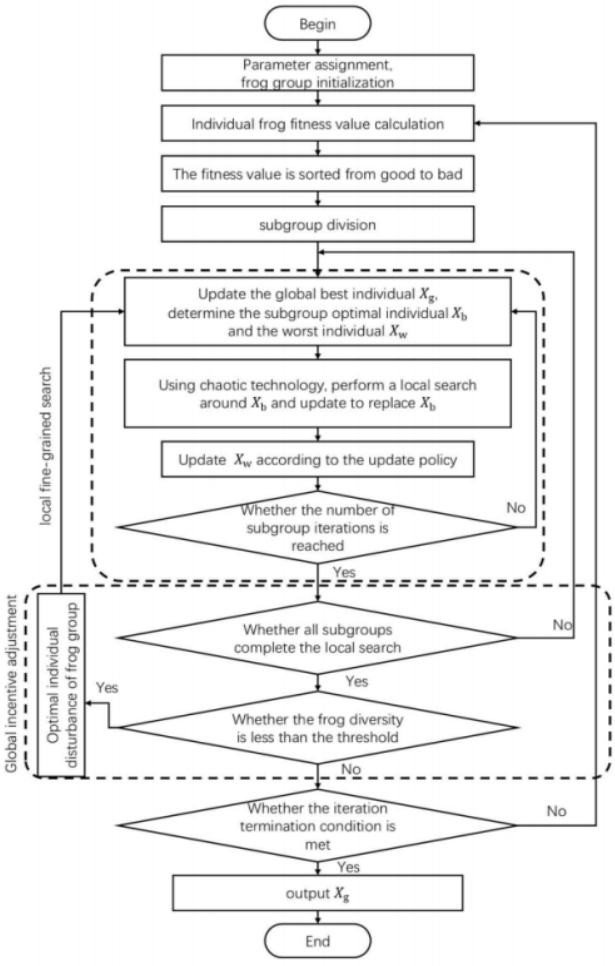


Figure 2. The flowgragh of ISFLA

In order to test the optimization effect of the ISFIA-based optimization model, we use the Windarling precipitation data as the assumed irregular weather conditions. We use this model to find a minimum number of species and the optimal species selection strategy under this constraint condition, so that the plant community we selected can exist stably in the assumed environment.

According to the suggestions of the existing literature, we set parameters in the algorithm as:

Table.3. Parameters and their settings

Parameters	Symbols	Value
Total Frog Population Size	F	200
Number of Frogs in Subgroup	M	10
Number of Iterations in Subgroup	Num local	10
Number of Frog Population Iterations	Num general	500
Frog Population Relative Diversity Threshold	μ	0.4
Excitation Factor	M_f	1.5

3.2. Result of model

The minimum number of species and the corresponding volatility Index are very similar. And except for the seventh result, the optimal species selection strategy is the same. With the calculation of the optimization model, we record the minimum error rate under different n values in the convergence process, and draw the graph as follows. It is clearly that when n≥6, the volatility index basically does not change, which means in our simulated environment, the minimum number of species that the plant community requires to benefit is 6, and as the number of species grows, The variation of the influence gradually tends to zero.

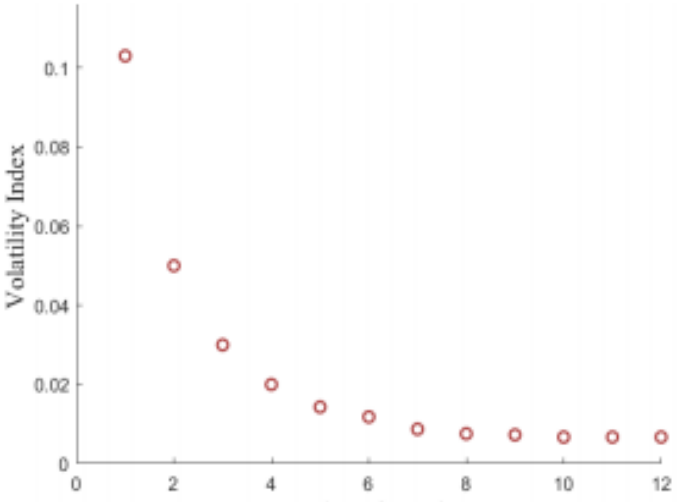


Figure 3. Number of Species

However, it must be emphasized that in the above solution process, the search space of the population selection strategy is limited to about twenty plants from the data source of Figure X, because a detailed data including a large number of species relationships is difficult to obtain. Therefore, the above results are strictly a simulation. Although the Windarling data are used, the simulation results cannot be considered to be significantly related to the actual plant community conditions of Windarling. In the process of practical application, we should first clarify the actual species categories in the region and establish the coefficient matrix of competition and cooperation of different species, so that the obtained values are of practical significance. In addition, the minimum number of species and species selection strategy obtained by the optimization of the model can in some way provide suggestions for improving the plant population in an ecologically fragile area.

4. Sensitivity Analysis

We select a normal system in which 4 species living in an average environment, keeping the other factor stable, then set the pollution factor and the habitat reduction rate to 1%, 2%, 3%, 4%, 5% separately and take them into our biological diversity model respectively, thus for several certain medium competitive species, different r_i and different population of species are obtained. The growing behaviors are shown in the table below.

Table.4. Growing behaviors under different population of species

		r_i	population of species
pollution factor	1%	0.4	48
	2%	0.36	44
	3%	0.33	42
	4%	0.31	38
	5%	0.3	33
habitat reduction rate	1%	0.4	44
	2%	0.39	42
	3%	0.41	41
	4%	0.38	40
	5%	0.39	39

We find that when pollution factor increases, the average plant growth rate decreases significantly and the average population of species decrease also. Moreover, with the increment of the pollution factor, both the whole rate and the total number of plants decrease. When the habitat reduction rate increases, the population of species goes down significantly and average growth rate stays the same overall. The reason may be that the rise in pollution factor has made the model more sensitive to the drought change when time increases, which means the drought adaptability decreases significantly. The rise in the habitat reduction rate makes our model more inclined to have a more limited max population, but at the early time its growth rate remains the same. Meanwhile, the sensitive species shows a more evident decreasing trend and the drought adaptability of a plant community become worse.

5. Strengths and Weakness

5.1. Strengths

1). The plant relationships model was developed on a certain theoretical basis, and the parameters of the model were carefully selected to make the model as close to reality as possible.

2). In building the model, a series of complex but meaningful preprocessing exercises resulted in NDVI data, which is much clearer and more intuitive.

3). The sensitivity analysis of the model demonstrates the effectiveness of the model under different parameter combination and prove the robustness of the model.

5.2. Weakness

1). The time lag between soil moisture and precipitation was not considered in the modeling process, resulting in a slight deviation between the result and the actual value.

2). We only consider the precipitation factor in climatic conditions and do not consider the influence of other factors in nature.

6. Climate change analysis

One question we also need to address is how the number of species in the plant community affects our conclusions as droughts increase in frequency and become more severe. In real life, the arid and semi-arid areas of Australia have suffered many bushfires caused by climate drought. Wildfire vegetation was reduced to ashes overnight. It can be seen that when the frequency and intensity of drought increase, the growth of plant community will show different degrees of skew.

Therefore, although our model can derive the optimal combination of steady-state growth of vegetation communities under different precipitation conditions. However, when the frequency and intensity of drought increase, the mortality rate of vegetation increases and the growth rate becomes

negative, which will break through our model. Therefore, we need more models to detect the relationship between environmental changes and plant growth so as to predict the optimal value, which will become the top priority of related research work in the future.

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