Plant Community Succession Based on Metacellular Automata Modeling

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Abstract. To explore the relationship between the number and type of species in a plant community and the community's adaptation to arid environments, we developed a cellular automata model that maps the various factors involved in individual plants in the community to a basic model, and we used the model to establish a direct relationship between individual attributes and the overall phenomenon, describing changes in the plant community over time. We used an iterative approach of global probability maps to study competitive relationships and reproductive processes among plants. Specifically, we consider not only the local state around individual cells, but also the global state of all cells in the entire simulation space, which will make it easier for us to consider the scope of influence of individual plants, facilitate the overall planning of plant reproduction and interspecific competition, and simplify the model while ensuring simulation.

Keywords: Metacellular automata; plant communities; global probability maps.

1. Introduction

With global climate change, extreme weather events, such as droughts, are occurring more frequently. Higher biodiversity can buffer the impact of a single drought event by increasing the resistance of ecosystems to loss of ecosystem function due to drought or by restoring ecosystem function after a drought event. However, drought may also increase the risk of species loss in plant communities. Different plants respond differently to drought, and plant communities with different numbers of species have different adaptive capacities to drought. Species complementarity (less competitive or more facilitative interactions between species) is an important mechanism for maintaining species diversity and stability under drought conditions with beneficial effects [1]. Research on this issue contributes to the long-term survival of plant communities and the artificial construction of plant communities that can withstand the threat of extreme climatic events.

2. Computational Simulations of Plant Species Competition

How large numbers of competing plant species manage to coexist is a major question in community ecology. The classical explanation is that each species occupies its own niche. Studies have suggested that plants segregate along various environmental niche axes, including gradients of light, soil moisture and root depth, and that partitioning of soil nutrients occurs. Niche separation along environmental axes plays a more significant role than has been previously appreciated [2].

In the study by Alder et al. (2007), classical coexistence theory was used to reframe the debate in terms of stabilizing mechanisms (niches) and fitness equivalence (neutrality). The neutral model is a special case where stabilizing mechanisms are absent, and species have equivalent fitness. Instead of asking whether niches or neutral processes structure communities, they advocate determining the degree to which observed diversity reflects strong stabilizing mechanisms overcoming large fitness differences or weak stabilization operating on species of similar fitness. They combine data on per capita growth rates with models to: (i) quantify the strength of stabilizing processes; (ii) quantify fitness inequality and compare it with stabilization; and (iii) manipulate frequency dependence in growth to test the consequences of stabilization and fitness equivalence for coexistence [3].

In the study by Schöb C et al. (2013), mountain ranging in dry environments was particularly suitable for exploring the relationships between environmental conditions, plant phenotype and plant– plant interactions. They hypothesized that different environmental stressors will differently affect the physiological status of a nurse plant. In an observational study, they measured a series of functional traits of Arenaria tetraquetra cushions as indicators of its physiological status (e.g. specific leaf area, relative water content [4].

An 11-year competition experiment conducted by R et al. (2007) on six grassland perennial plant combinations showed that resource competition theory can generally predict the long-term outcome of competition [5].

These papers provide computational simulations of competition between different plant species and serve as a reference for our model.

3. Metacellular automata modeling of plant community succession

When a plant community is exposed to a variety of irregular weather cycles, such as irregular drought, the changes over time are a complex and stochastic process, which should take into account the number and attributes of species, the interactions among species, and the effects of irregular drought environment. We built a cellular automata model to map various factors involved in individual plants in a community to the basic model and used the model to establish a direct relationship between individual attributes and overall phenomena and describe the changes of plant communities over time [6].

3.1. Data collection

The soil properties and climate conditions in different regions are different, and the changes of soil water content will be different.

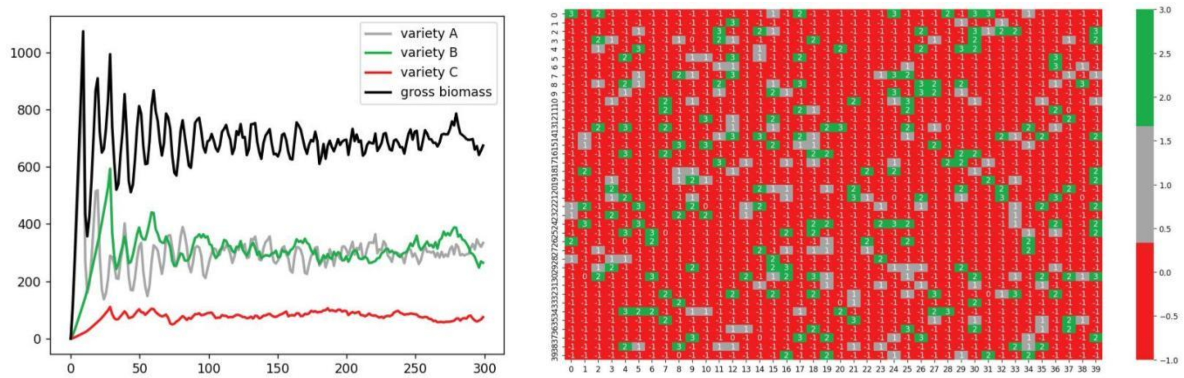

Fig. 1 Land contamination (-1 indicates contaminated land)

As can be seen from the Figure 1, the decrease of total biomass caused by pollution has almost equal effects on A and B, with A's maximum growth ability limited and B's maximum competitiveness limited.

3.2. Modeling plant community succession

Cellular Automata (CA) is a discrete space and discrete time computational model with parallel processing capability, which has been widely used in simulation and research in biology. Each unit of the CA, called a "cell," undergoes state transitions through rules and interacts with surrounding cells. Classical CA models are characterized by their simplicity, ease of implementation, ability to describe nonlinear phenomena, and good visualization properties.

Based on the advantages of CA in ecological research, we selected this model as a research tool, optimized it and adjusted its parameters to make it more suitable for describing the relationships between individuals of different plant species in plant communities, and studied the role of the number of species in the community on the overall adaptability of the community to drought environment.

It is worth mentioning that we take the iterative approach of global probability map to study the competition relationship and reproductive process among plants. Specifically, we not only consider the local state around a single cell, but also consider the global state of all cells in the whole simulation space, which will make it more convenient for us to consider the influence range of a single plant individual and is conducive to the overall planning of plant reproduction and interspecific competition and simplify the model while ensuring the simulation.

3.2.1 The amount of plant state in the cell

- **aboveground biomass M1**, which is the amount of space occupied by plants and the amount of biomass. In the model, plant competition factors will be affected by above-ground biomass, that is, if a plant has a higher above-ground biomass than its surrounding plants, then it has a greater chance of occupying more space in the next iteration.
- **underground biomass M2 (root system)**, which represents the size of the water absorption capacity of the plant, will affect the water acquisition of the plant in one iteration in the model. In arid environments, the greater the amount of underground root system of a plant, it is able to absorb more water from the soil, thereby improving its own survival.
- **moisture storage capacity M3**, which is the amount of water that plants store. In a dry environment, the water storage of a plant will continue to decrease, and if the plant's water storage drops to a very low level, then it may not survive any longer.
- **water absorption M4**. The water absorption capacity is affected by the amount of underground roots, and a larger amount of underground roots enables the plant to absorb more water from the soil, thereby increasing its survival rate.

The combination of these state quantities affects each plant's ability to survive and reproduce. In the model, we treat them as state quantities of individual plants that change continuously over time to simulate real plant growth and succession processes.

3.2.2 Iterative details of metacellular automata

In each temporal iteration, individual plants are affected by the environment, and the most important factor is soil water content. In arid environments, soil water content decreases rapidly, resulting in an accelerated reduction in water storage by individual plants.

At the same time, individual plants use part of their water resources for the growth of state mass, including aboveground biomass, belowground root mass and water storage, based on their previous decisions. At each time iteration, the individual plant needs to make a new decision to determine the proportion of growth for each state quantity, which will affect the growth, competition and reproduction ability of the individual plant in the next time iteration.

For each cell, we can calculate the state of that cell in the next iteration based on the state of the surrounding neighbors and the information of the individual plants. If the current cell is empty and is also empty in the surrounding neighbors, it will remain empty in the next iteration. If there is a plant in the current cell and there is no plant in the neighborhood, the plant will continue to exist (if its growth period is not up).

If the current cell is empty and surrounded by plants, the probability that the cell will be some plant in the next iteration is the expansion factor of that plant divided by the sum of the expansion factors of all neighbors plus one. This means that a plant with a higher expansion factor will be more likely to grow in an empty cell.

If there are plants in the current cell and also in the surrounding neighbors, then its state in the next iteration depends on the survival factor S and the competition factor Q of the individual plants. Suppose that the sum of survival factors for conspecific plants in all neighbors is S’ and the sum of competition factors in all neighbors is Q’.

The probability that the cell remains as it is in the next iteration is:

$$P = (S + S')/(Q + Q') \tag{1}$$

If the cell is invaded by another plant in the neighborhood, then its state will change to that of the plant. In this case, the probability that the cell is invaded is the competition factor of the other plant divided by its own survival factor plus the survival factor of the same species in all neighbors plus the sum of the competition factors in the neighbors.

The combined effect of these rules will determine the state of each cell in the next iteration, thus simulating the dynamic evolution of the entire plant community.

The advantage of the global probability graph model can be explained in the following two ways.

First, this model uniformly takes into account plant reproduction and interspecific competition. In past cellular automata models, it is common to consider these two effects separately, which often leads to insufficiently accurate fitting effects. In fact, in nature, competition between populations is achieved through the reproduction of populations. Therefore, the global probability graph model uses a combination of the expansion factor and the survival factor, taking both effects into account, which makes the model more accurately simulate the real situation. Doing so not only simplifies the model but also improves its accuracy.

Second, the global probability graph update iteration means that we can simultaneously detect the species class of all lattices with each update of species status. In the traditional cellular automata model, the state of each lattice needs to be updated in a certain order. This means that when new rules are added to the model, the update order needs to be modified, which causes the model to become complex and difficult to extend. In the global probability graph model, we can examine the whole model at the same time, which simplifies the model and improves the scalability of the model.

In summary, the global probability map model simplifies the model and improves accuracy by considering both plant reproduction and interspecific competition. In addition, the global probability graph update iteration also improves the scalability of the model, making the model easier to modify and adjust.

4. Plant community scoring model

To assess the relationship between the number of species in a community and the community's ability to adapt to arid environments, we designed the following parameters:

- Community competition index:

In the global probability graph, each grid is actually a probability space. The sum of information entropy of each unit of the global probability graph of the whole community is calculated to represent the number of resources wasted by the community for competition and reproduction.

- Community development index:

the total biomass of the community after the impact of irregular drought environment was compared with the total biomass of the community under constant state, and the relative reduction value was calculated to represent the resilience of the community.

- Community stability index:

The community was placed in irregular weather conditions and the number of iterations of its information entropy returning to zero was recorded (all cells were cleared to zero or only one species was left) to characterize the sustainable development ability of the community.

Considering the three evaluation indexes of the community, we set the comprehensive adaptability index of the community.

In the Figure 2, we structure the modeling process and add random variables to eliminate the influence of irrelevant parameters, so as to ensure that our attention is focused on the correlation between the species and number of plants and the ability of the community to adapt to drought.

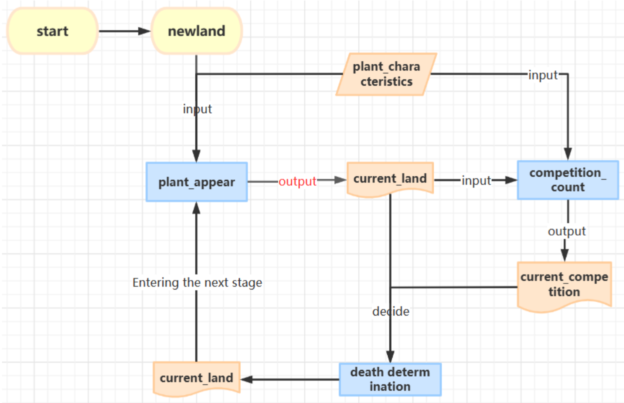

Fig. 2 Model Overview

In our plant model, when two species meet, they compete for the remaining soil water content, reflecting the competition between populations.

When the population is three, we set different stable environments and run the cellular automata model to obtain the following stable population model. Below, we treat the community with the same irregular arid environmental conditions. A: Drought-escaping plants, B: drought-resistant plants, and C: drought-resistant plants were selected for the following simulation.

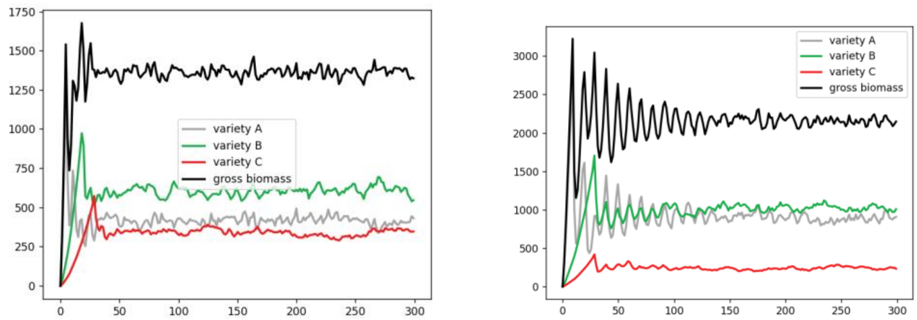

Fig. 3 Stable Population Model 1 and 2

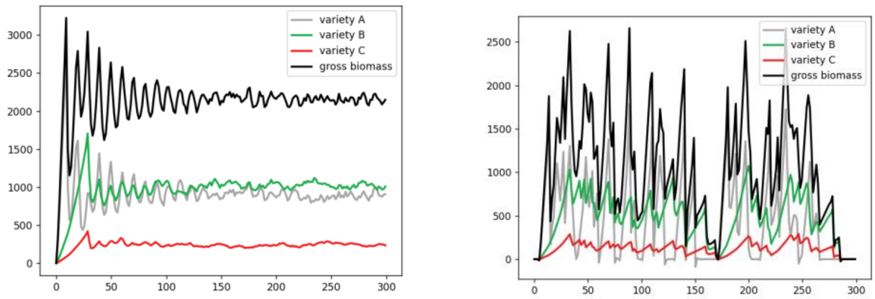

Fig. 4 Stabilization patterns 1 and 2 affected by unseasonal droughts.

It can be seen from the Figures 3 and 4 that after the community is affected by irregular drought, the general normalized biomass change of the community will show large fluctuations, and due to our previous assumption.

Considering that plant communities in reality contain more individuals and are able to interact with larger environments, we extend the original model in the first question in both time and space dimensions.

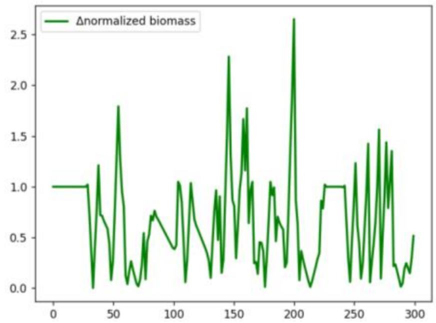

Fig. 5 Expanding Living Space Area (30*30)->(50*50)

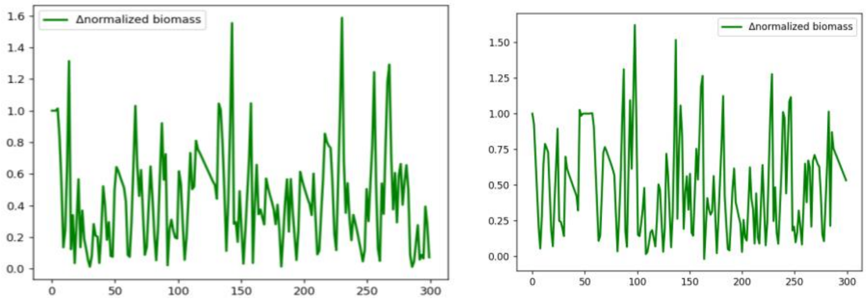

Fig. 6 After adding the new species, D and E

It can be seen from the Figures 5 and 6 that increasing living space has little effect on plant drought resistance index (normalized biomass variation) but increasing the number of species can significantly improve drought resistance index.

As shown in the previous plant model, we defined different types of plant species, such as: drought-resistant, drought-resistant, and drought-resistant. When running cellular automata model for simulation before, we added more random variables into the selection of species, but now we are more interested in the type of species, and we want to know the impact of a certain type of species on the community model. In the following simulation, we fixed several species of a certain type and ran the cellular automata model again. To measure the impact of certain types of species on a community.

Under ideal rainfall conditions (ideal stable rainfall conditions)

A: Drought escape plants B: Drought-resistant plants C: Drought-resistant plants

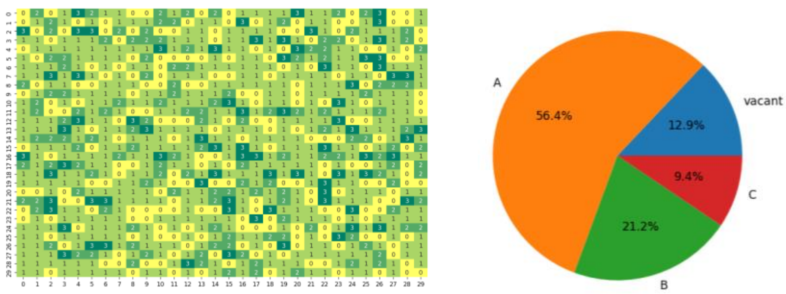

Fig. 7 Global Probability Map - Phase 2

Initially, it is known from Figure 7 that species A (labeled 1) will soon occupy the entire area.

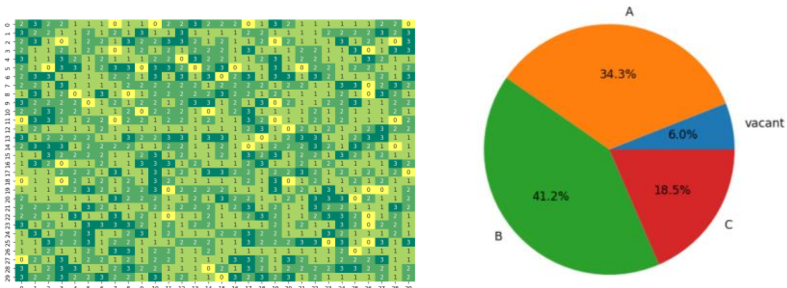

Fig. 8 Global Probability Map - Phase 20

As can be seen from Figure 8, over time, when A and B are approaching, A is at a competitive disadvantage and is gradually eliminated (dying due to lack of water), while C always keeps growing steadily, which is consistent with the actual situation and further confirms the reliability of our model.

Based on our model, we find that:

1. With the deepening of drought, our drought-resistance index (normalized biomass change) was larger on the whole, indicating that the stability of the community was unbalanced.

2. With the increase of the number of species, the change of the normalized biomass was small on the whole, which proved that the community was stable.

3. In extreme weather conditions, the main reason for the unbalance of community stability was the fluctuation of biomass of drought-escaping plants, which was determined by the characteristics of rapid growth and short life span of drought-escaping plants.

5. Summary

Compared with the traditional differential equation model, the metric automata model has more degrees of freedom and can better describe some complex nonlinear dynamical systems. Traditional differential equation models usually use mathematical formulas to describe the state and evolution laws of the system, so there are some limitations in describing and modeling the system. The cellular automata model is a discrete dynamical system based on lattice points, which can describe the behavior of the system by discrete states and evolutionary rules. Compared with differential equation models, the cellular automata model has a greater degree of freedom because it can simulate more complex nonlinear systems and phenomena, including phase transitions, self-organization, group behavior, nonlinear fluctuations, and other phenomena that cannot be described by traditional differential equation models.

The accuracy and predictability of the model can be improved by adding more and more complex parameters, such as the ability of the plant to change its decisions over time iterations and to inherit decision-making attributes from its parent plants. However, before adding more parameters, careful consideration should be given to data collection, computational complexity, parameter interpretability, and model accuracy, and to ensure that the benefits of adding more parameters outweigh the costs. If the decision is made to add new parameters, care needs to be taken to maintain model simplicity and interpretability, and to conduct adequate validation and testing to ensure model accuracy and reliability.

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