Establishment and analysis of biodecomposition model based on cellular automata

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Abstract. In order to explore the relationship between the number and type of species in a plant community and the adaptability of the community to drought environment, we built an optimized cellular automata model to simulate the iteration of individuals in the community. We simplified the model and added random parameters to focus on the correlation between these two quantities, which is also the methodological philosophy of our global model architecture. After many simulations, we found that: the adaptability of community to drought with the increase of species number, effects of species type on community adaptability 3. In the face of current pollution and habitat loss, our model has some implications for strategies to increase long-term community survival.

Keywords: Cellular automata; community succession; model of plant.

1. Introduction

With global climate change, extreme climate events such as drought occur more frequently. Higher biodiversity may buffer the impacts of a single drought event through increasing the resistance against the drought-driven loss of ecosystem functioning or the recovery of ecosystem functioning after the event. However, drought may also increase the risk of species loss in plant communities. Different plants respond to drought in different ways, and plant communities with different numbers of species have different adaptive abilities to drought. Species complementarity (less competitive or more facilitative interactions between species) is a crucial mechanism to maintain species diversity and stability and produce beneficial effects under drought conditions [1]. The research on this issue is helpful for the long-term viability of plant communities and the artificial construction of plant communities that can resist threats from extreme climatic events

In this paper, we are required to build a mathematical model to identify the changes of a plant community over time as it is exposed to various irregular weather cycles and develop a mathematical model considering the long-term interactions of a plant community and the larger environment. Firstly, simulate plant community succession. We built a cellular automata model to map various factors involved in individual plants in a community and used the model to establish Team # 2322048 Page 4 of 25 a direct relationship between individual attributes and overall phenomena, and describe the changes of plant communities over time. Then we built a model of plant. In order to better understand the adaptation of communities to drought conditions, we intentionally highlight the ability of plants to change according to environmental changes in the model. And we developed plant community scoring model. We designed some parameters to assess the relationship between the number of species in a community and the community's ability to adapt to arid environments.

2. Cellular automata model of plant community successionSection Headings

Based on the existing literature, the following assumptions are made. Aboveground biomass, underground biomass (root system), moisture storage capacity, water absorption, the expansion factor, the survival factor and water consumption are related. Such simplification and abstraction is necessary to make the model more concise and to better abstract the relationship between the number and type of species and the resilience of communities to drought conditions; Assume that water is absorbed only in rainy days, but not in dry weather.

And if there is no underground water source and the water absorption of plants only depends on the weather, the soil water content will decrease rapidly when there is no rain. So plants get far less water from the soil when it's not raining than when it's raining.

Assume that there is no intraspecific competition. When we consider problems in the context of a community, highlighting the effects of interspecific competition while ignoring intraspecific competition allows us to better focus on the relationship between interspecific relationships and community resilience.

2.1. Model fundamentals

Cellular automata is a type of discrete dynamical system that consists of a grid of cells, each of which has a finite number of states, and evolves in discrete time steps. The evolution of the CA is determined entirely by the initial configuration of the cells and the rule for updating their states.

Any point in space in the neighborhood of 3D-Von Neuman type cell at $p=(x,y,z)$, according to the law of conservation of mass of diffused matter, from time t to at $t+\Delta t$, the content of i substance $Mi(p,t)$ in the cell diffuses in all directions the following vector equation is satisfied between the fluxes:

$$M_i(\boldsymbol{p},t+\Delta t)\& = M_i(\boldsymbol{p},t)+\Delta t\sum_{k=1}^{6} A_k(\boldsymbol{p})\left[J_{\text{in},k}^{i}(\boldsymbol{p},t)-J_{\text{out },k}^{i}(\boldsymbol{p},t)\right] \tag{1}$$

Where: Ji out,$k(p,t)$ and Ji in,$k(p,t)$ respectively represent from time t to time $t+\Delta t$, along the direction k the diffusion flux of each substance flowing out and into the cell; Δt is the time step increment; $Ak(p)$ is the area of the cell diffusion surface in the k direction.

2.2. Data Description

2.2.1 Soil Water Content Change Data Du

The following is the data of soil water content provided by some authoritative papers at the time of drought disasters in different places: Peters et al. (2013) conducted a study in a field in Nebraska, USA, in which soil water content was monitored over a long period of time, and found that soil water content was reduced by an average of about 30% during the 2002 dry period. Yao et al. (2015) conducted a study in the Loess Plateau of Longdong, China, and monitored the changes of soil water content from 2009 to 2011. The results showed that the degree of soil water content reduction during drought was positively correlated with the degree of rainfall reduction, with an average reduction of 35.6% in the year with the lowest soil water content during drought. Suwei et al. (2013) conducted a study on 170 arid regions around the world and found that the average reduction in soil water content was between 30% and 50% in most arid regions. These studies provide some authoritative data on changes in soil water content during drought. However, it should be noted that the soil properties and climate conditions in different regions are different, and the changes of soil water content will be different.

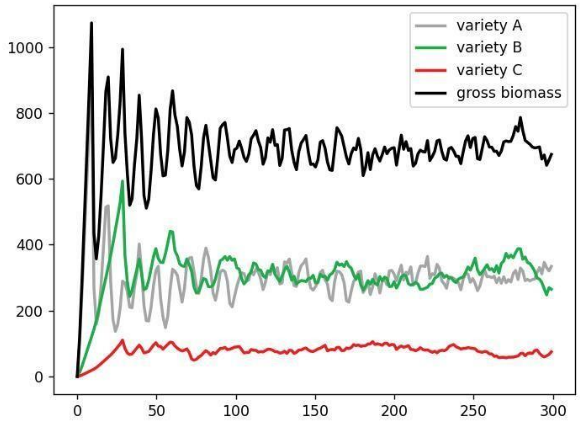

Fig. 1 Comparison of different types of data

As can be seen from the figure, 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.

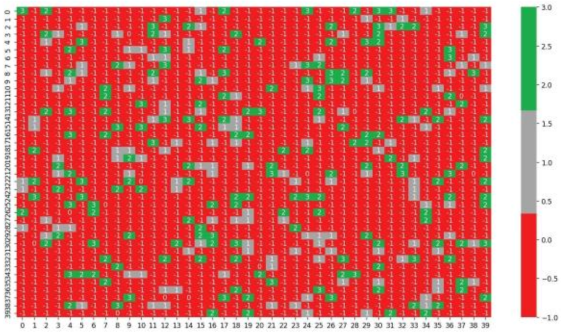

Fig. 2 -1 represents contaminated land

2.2.2 Root development and drought adaptability data

According to a study published in the Journal of Experimental Botany in 2018, the researchers evaluated the degree of root development of plants under different drought levels and found that the degree of root development was significantly correlated with the drought adaptability of plants. Mathematical modeling was used to further validate the results.

According to a 2016 study published in Soil Biology and Biochemistry, researchers studied root development and soil water content of a variety of plants in the arid region of Utah. The results showed that with the deepening of soil drought, the root system of plants became more and more developed. This phenomenon may be that plants actively increase root growth in order to obtain better water.

According to a study published in Frontiers in Plant Science in 2020, the researchers used a computer model to simulate changes in root development under different levels of drought. Our results showed that higher levels of drought were associated with more developed root systems, and that the degree of response varied among plant species. Data on a variety of plant species were mentioned in the study, including wheat, corn, pea, and others.

2.3. Simulating 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.

2.3.1 Plant State Quantity in a 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.

2.3.2 Iteration Details of the Cellular 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:

$$P = (S + S')/(Q + Q') \tag{2}$$

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.

3. Model Application

To solve the correlation between the species and number of plants and the ability of the community to adapt to drought, 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.

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. The experimental results are shown in the figure below:

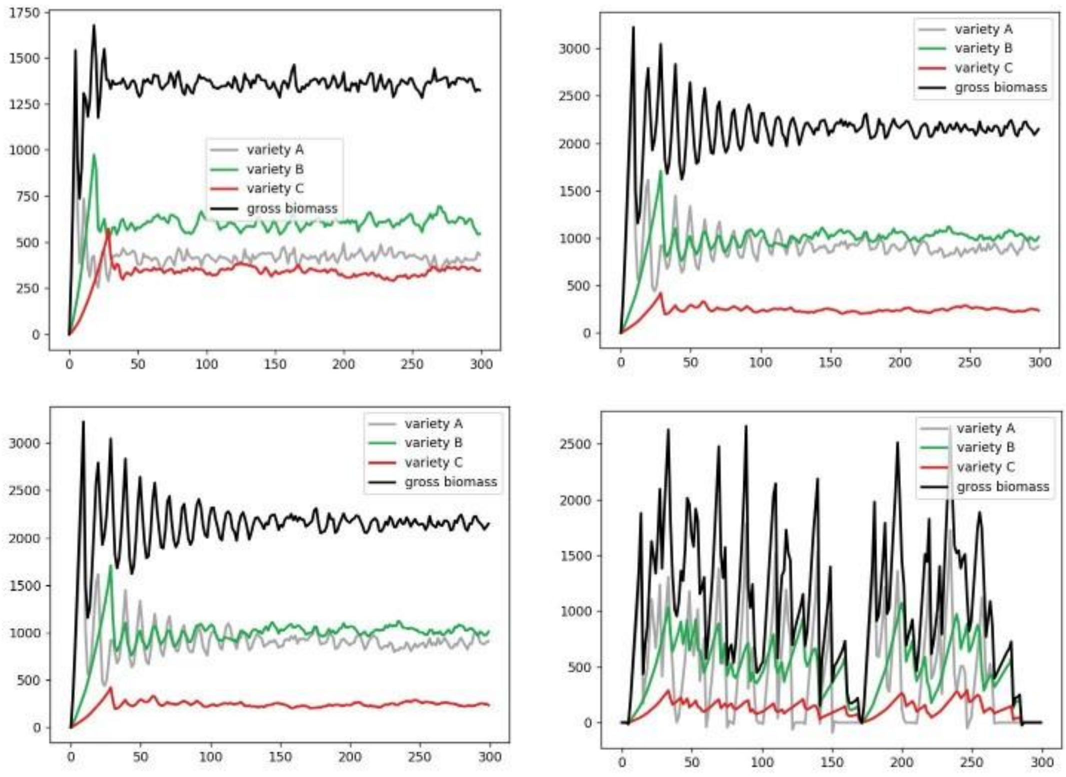

Fig. 3 Stable Population Model 1 and Model 2; Stable Model 1 and Model 2 subjected to irregular drought

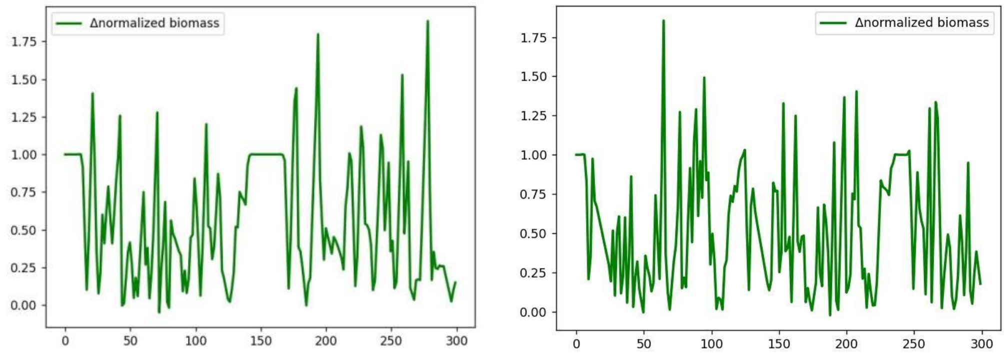

Fig. 4 Model 1 and Model 2 Indicator Changes Over time

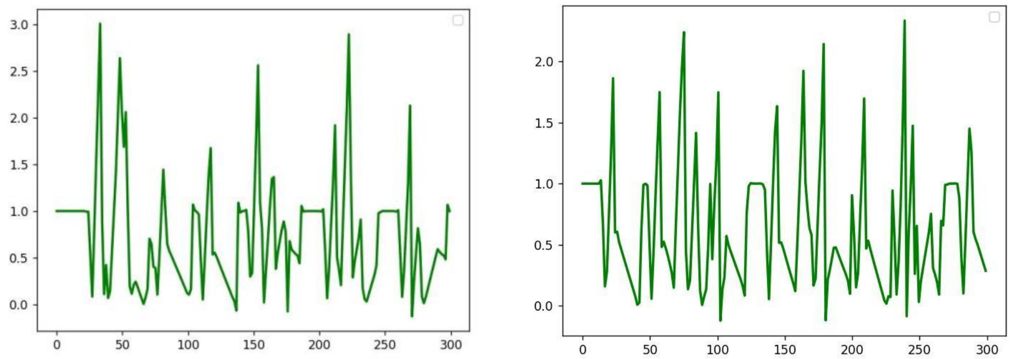

Fig. 5 Three species under extreme drought conditions and Five plants in extreme drought conditions

In the real environment, the survival of the plant community will be affected by pollutants and habitat reduction. In the model, we simulated the impact of pollution on the community by accelerating water loss through the life span of the polluted plants, and simulated the reduction of habitat by setting some cells as unable to grow. The following is the iterative simulation of the community under these circumstances.

Based on our model, we find that: 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; 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; 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.

4. Summary

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. 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.

And we built a model of plant. We wanted to focus more on the relationship between species number and environmental adaptability. According to the data and conclusions in the previous paper, the above attributes are not only affected by environmental factors, but also by the characteristics of the plant itself. And we found some data supporting for plants adjusting their survival strategies in response to environmental changes. In order to better understand the adaptation of communities to drought conditions, we intentionally highlight the ability of plants to change according to environmental changes in the model. To this end, we designed decision attributes of plants to make them more "intelligent", and also to enable precise classification of plants and better study the role of certain types of plants on community survival.

Compared with the traditional differential equation model, cellular automata model has more degrees of freedom and can describe some complex nonlinear dynamical systems better.

The traditional differential equation model usually uses mathematical formula to describe the state and evolution law of the system, so there are certain limitations on the description and modeling of the system. The cellular automata model is a kind of discrete dynamic system based on lattice points, which can describe the behavior of the system through discrete state and evolution rules.

Compared with the differential equation model, cellular automata model has greater freedom, because it allows the simulation of more complex nonlinear systems and phenomena, including phase transition, self-organization, group behavior, nonlinear fluctuation and other phenomena that cannot be described in the traditional differential equation model.

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