Problem Chosen	2023 MCM/ICM Summary Sheet	Team Control Number
A		2307931

Simulation Analysis: Plant Community During Drought

Summary

How a plant community survives in the face of irregular weather cycles, especially in times of drought, has been a hot topic in ecology. To address this question, our team has developed a mathematical model that provides some answers. By studying the effects of different species and environmental factors through simulation, we have found results that may be key to the long-term survival of plant communities under drought conditions.

First, to address the problem of predicting changes in plant communities under fluctuated and irregular weather cycles, we propose the Drought-Plant Cellular Automaton Model. We set the drought degree in each month based on the SPEI of several regions from 2001 to 2020, and simulated the survival and reproduction of the herb-shrub-tree plant community under irregular drought conditions. From this we derived how the plant communities evolve under various drought conditions.

Based on extensive studies of tree, shrub and grass interactions in different climates, the evolution of plant communities during drought is characterized by species interactions. We explored the effect of species diversity on drought tolerance and found that species numbers enhance community biomass when they initially increase, but biomass also decreases with increased competition caused by continued increases in species numbers. Therefore, we obtained that for plant communities under drought conditions, the number of species best suited to survive is around 20 in moderately dry regions, while about 40 species in mild dry regions.

The types of species in the community also affect the simulation results. Herbs having shallow root systems are more resilient, while trees are more resistant and less resilient. We investigated the effects of increasing drought frequency and variability and found that more severe and frequent droughts result in more rapid plant mortality and reduced reproduction, and have different impacts on different types of vegetations.

In addition, we considered the effects of pollution and habitat reduction on plant communities, with pollution reducing reproduction rates and increasing mortality, and habitat reduction, such as that caused by desertification, directly affecting community reproduction and individual numbers. We also considered the effects of factors such as fire and herbivore feeding on plant communities, and simulated the effects of fire on plant populations by building a fire model.

Finally, sensitivity analysis showed that our model is highly robust. Moreover, in response to these results, we propose a set of measures to ensure the long-term viability of plant communities, including drought countermeasures, species diversification, controlling species populations, reducing pollution, and preventing desertification.

In addition, our model is very easy to implement and extend, only need to import the drought degree data and plant cover data of different regions, and simply adjust a few parameters in our code, the model can predict the evolution of plant communities in different regions under different conditions, which provides some help to protect the ecological environment from the perspective of protecting plant communities.

Keywords: Plant Community; Drought Coping; Drought-Plant Cellular Automaton; Simulation Prediction; Sensitivity Analysis; Sustainability.

Contents

1 Introduction

1.1 Problem Background

Different regions of the world have different environments, and there are many places with harsh natural environments that are prone to disasters such as droughts, heavy rains, and wildfires; at the same time, human impacts on ecology, such as overgrazing, indiscriminate logging, and pollution caused by industrial production, cannot be ignored. Environmental interactions have an important impact on plant abundance and diversity, while plants are constantly evolving to adapt and change their environment.

In this paper, we attempt to explore a visual mathematical model to simulate the changes of plant communities considering different factors. First, we need to build a mathematical model to analyze the changes of the community under various and irregular drought. Secondly, based on this model, we are required to consider the effects of species number and species type on plant communities under different drought conditions to find out the optimal species number. Furthermore, taking the impacts of the larger environment into consideration, we need to analyze once again the impacts of different factors on the changes of plant communities.

1.2 Literature Review

This question is primarily concerned with studying the response of plant communities to arid environments. In recent years, the research direction is mainly divided into two parts: one is the impact of different arid environments on the survival and reproduction of plants and the relationship between species, and the other is the mixed impact of macro-environmental interactions on plants.

- First, we gathered background on the drought. Drought is generally defined by drought frequency, severity, and duration[1]. Drought is a natural disaster caused by intense and persistent rainfall deficits[2]. The Drought Index is used as a surrogate for tracking and quantifying drought[3]. Beguería et al. demonstrated the use of the SPEI index to quantify the robustness of drought and expressed the fluctuation of drought by calculating the variance[4]. The degree of drought varies from place to place. For example, Andreadis et al. showed that the drought in the United States in the 20th century became shorter and less frequent in most cases[5]. Li et al. showed that the western part of North China has become wetter in recent decades but the Northeast is getting drier[6]. There are many research directions on drought. For example, Zandalinas et al. studied the adaptation of plants to drought environment through specific physiological responses from the perspective of genes[7]. Ploughe et al. studied the response of plant systems to drought from the perspective of community[8]. Skarpe studied savannah environment and species interactions from a systems perspective[9].
- Second, we collected drought effects on plants, broken down into interspecific effects and biodiversity. Interspecific interactions are an important mechanism for plant communities to respond to the environment. There have been some previous studies on the quantification of interspecific relationships and their effects under different drought degrees. Gómez-Aparicio proposed that the life forms of

adjacent species have an important impact on the emergence, reproduction and growth of plants[10]; Ploughe et al. found that the degree of drought will change the intensity of competition and promotion between species[8]; Lorena Gómez-Aparicio further found the neighborhood effects and interaction factors among herbs, shrubs and trees were calculated by meta-analysis[10]. Biodiversity in plant communities plays a role in drought resistance. Backhaus et al. found that high-frequency mild drought can increase the resistance of plant communities[11]. Scholars have verified through field experiments that appropriately increasing biodiversity can significantly promote drought resistance. Forrester found that mixed forests help to utilize light, soil and other resources[12]; Silva Pedro et al. found that increased species diversity is conducive to resistance to natural disturbances[13]. Regarding the mechanism by which biodiversity is beneficial to drought resistance, Xavier Morin et al. found that the increase in diversity caused response asynchrony and enhanced temporal stability[14]; Vogel et al. and Tilman et al. found that increased species richness made community resistance Stability increases, restoring force stability decreases[15, 16].

- Finally, we collected the effects of the larger environment. Van Langevelde et al. proposed a positive feedback relationship among fire, herbivores and plants[17]. Brooks et al. showed that the destruction of species habitat by human activities can reduce species richness and even lead to species extinction[18]. Prabhat Kumar Rai showed that PM or dust deposition can reduce plant diversity by inhibiting plant photosynthesis[19]. Mapaure et al. quantifies the significant changes in species composition and structure caused by soil pollution in semi-arid regions[20].

1.3 Our Work

Under the assumption that interspecific interactions are the main mechanism by which biodiversity acts on the drought resistance of plant communities as well as other natural disturbances, this paper establishes a periodic meta-cellular automaton to simulate interspecific interactions for the study.

Task 1. We use a Moore cellular automaton to simulate the environment of the plant communities to observe their changes. We select several regions with typical climate features as the environment for plants to grow. Then by multivariate analysis of the biotic and abiotic factors, we formulate the State Transition Rules. By running the cellular automaton under different environments, we simulate the changes of plant communities in 5 regions.

Task 2. We add the effect of species number on resistance and resilience to the State Transition Rules, thus obtain the optimal number of species for plant communities through simulation. In addition, we simulated the evolution of plant communities with different species types and derived the impact of species types on plant communities.

Task 3. We adjust the fluctuation and frequency of occurrence of drought degree to simulate the changes of communities under different drought conditions, and obtain the optimal species number for community survival under this condition.

Task 4. Considering factors such as fire, pollution, and habitat reduction, we adjust our cellular automata model and repeat the procedure above to predict the changes in plant communities with various factors. Accordingly we give suggestions to ensure the long-term survival of plant communities, as well as the impact on the larger environment.

2 Preparation of the Models

Considering that practical problems always contain many complex factors, first of all, we need to make reasonable assumptions to simplify the model, and each hypothesis is closely followed by its corresponding explanation:

2.1 Analysis of Problems

The survival and reproduction of plants are influenced by both biotic and abiotic factors.

For one thing, there are interspecific interactions between plants that bring about both positive and negative impacts: plants may compete with neighbors for resources, thus creating a competitive relationship that reduces the survival and reproduction rates; plants may also be shaded by neighbors to reduce their exposure to drought, thus increasing the viability. For another, various environmental factors may also act on the evolution of plant communities, for example, higher drought levels may adversely affect the growth and reproduction of plants.

Moreover, the changes of plant communities is highly dynamic in time and space, with a dynamic balance between grassland and woodland from the temporal scale and similar to patchy dynamic systems from the spatial scale. Therefore, we need to develop a dynamic spatio-temporal model considering the effects of multiple aspects on plant communities.

2.2 Assumptions

We make the following assumptions about our cellular automaton simulation process:

1. **The time is set in the 21st century, and the data cited in the paper are reliable.**
   Explanation: The meteorological data cited in this paper are all from the 21st century (2001-2020), making the model more applicable to present-day simulation predictions.

2. **Plant communities can be classified into three categories: herbs, shrubs, and trees.**
   Explanation: Plant communities may contain plant types other than these three categories, but for the sake of simplicity of the model and applicability of the referenced data[10], we set the model in areas where plants can be classified into these three categories.

3. **The environment remains relatively stable and suitable for plant growth except for drought conditions.**
   Explanation: There is no natural disasters, and the soil in the model area retains roots or seeds that can produce herbs when conditions are suitable.

4. **Plants communities evolve from herbs to shrubs, then to trees when conditions are suitable, otherwise they degrade in reverse steps.**
   Explanation: The actual mechanisms of plant community evolution and degradation are more complex, and the most typical patterns are selected here for analysis.

5. **The volume of the plant community can be represented by the number of plants and biomass counted in the model.**
   Explanation: Based on the data of other thesis[21], we set the ratio of biomass for herbs, shrubs, and trees of equal area to 1:1.5:2.5 in the calculation.

Additional assumptions are made to simplify analysis for individual sections. These assumptions will be discussed at the appropriate locations.

2.3 Data Overview

Since the question does not provide us with data directly, we collect the weather data of the 5 regions for model construction, such as **the monthly temperature and precipitation, Standardized Precipitation Evapotranspiration Index(SPEI) for 20 years** and so on. Due to the large amount of data, it is not convenient to list them all, so visualizing the data for display is a good method.

Data Collection The data sources used in our paper are shown in Table 1.

Table 1: Data and Database Websites

Database Names	Database Websites
World Weather Information Service	https://worldweather.wmo.int/
Global SPEI database	https://spei.csic.es/database.html
Google Scholar	https://scholar.google.com/

Data Screening

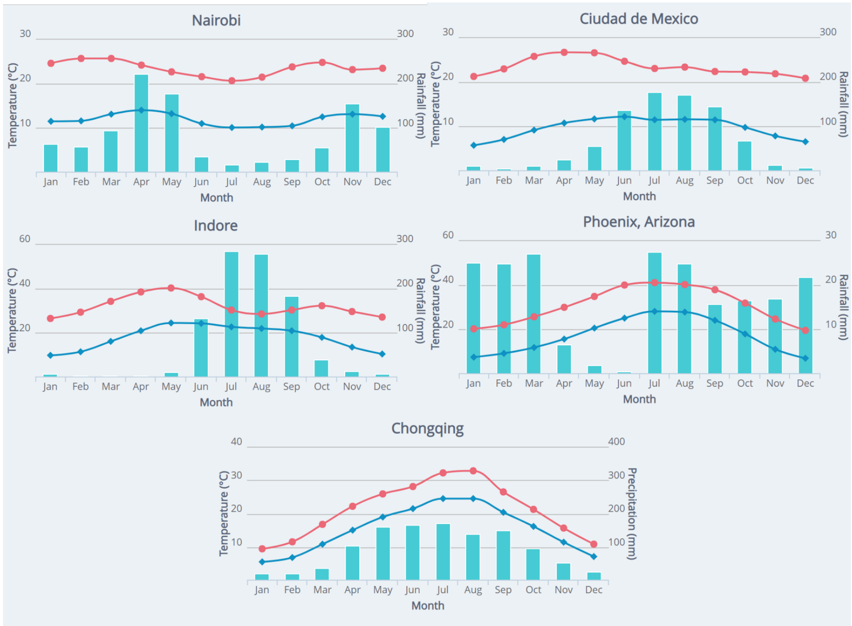


Figure 1: Temperature and Rainfall Data of 5 regions

1. We obtained SPEI data from the Global SPEI database for the last 20 years (2001-2020) for five areas: Nairobi(savanna climate), Ciudad de Mexico (tropical desert climate), Indore (subtropical monsoon climate), Phoenix (subtropical desert climate) and Chongqing (subtropical monsoon climate) are both regions where drought often occurs.
2. The selected regions contain almost all typical arid or semi-arid climates, and almost all possible drought frequencies and intensities are included, making the simulation of the model more representative.
3. The five regions selected are spread across the globe and have a large time span, which minimizes the influence of chance factors (such as unusually dry or wet climate in a particular region in a given year), thus making the model more applicable.

2.4 Notations

Some important mathematical notations used in this paper are listed in Table 2.

Table 2: Notations used in this paper

Symbol	Description
L	Size of the land
T	Number of iterations (in months)
n	Number of the species
d_i	Drought degree of the i^{th} month, ranging in [0,1]
c_{dry}	Drought offset coefficient
$N_1(i,j)/N_2(i,j)/N_3(i,j)$	Numbers of herbs/shrubs/trees in the Moore neighborhood of land in i^{th} row, j^{th} col
$S_{i,j}$	Survival interaction coefficient of type i land to type j land
$R_{i,j}$	Reproduction interaction coefficient of type i land to type j land
P_s	Possibility for the plant to survive
P_r	Possibility for the plant to reproduce
P_b	Possibility for the plant to burn

*There are some variables that are not listed here and will be discussed in detail in each section.

3 Prediction of Plant Community Changes

In this section, we will use cellular automaton to model plant-plant and plant-environment interactions to predict the changes of plant communities under various and irregular droughts. We conduct experiments for several regions with different climates and obtain results for several plant community evolutions.

3.1 Model Preparation

3.1.1 Model Principle

We select five regions with representative climates around the world as the background of the model (in no particular order): Nairobi, Kenya; Mexico City, Mexico; Indore, India; Phoenix, USA; and Chongqing, China. The selection of these five regions was based on the Global SPEI database for their drought levels from January 2001 to December 2020, and the World Weather Information Service for their precipitation and temperature statistics. By simulating the changes of plant communities in these five geographically and climatically diverse regions, we seek models with a higher degree of generalizability.

Many complex problems involve the interaction of a large number of individuals in a community. Plant survival and reproduction are influenced by the neighboring individuals and the environment. Therefore, the core of this problem is how to build a model to simulate the interactions between plant individuals. A cellular automaton is essentially a dynamic system defined on a cellular space, which is composed of cells with a finite number of discrete states. According to the State Transition Rules, the cells switch between discrete states along time. Thus, we can use the cellular automaton to simulate the changing process of plant communities.

The model we designed is called the Drought-Plant Cellular Automaton.

3.1.2 Model Assumption

- Environmental factors such as drought degree and soil are uniform in the modeled square tracts and do not vary by location.
- The climate of the area is relatively stable, and the degree of aridity is cycled roughly on an annual basis. The differences in drought levels corresponding to specific months are within acceptable limits between years. Therefore, we can average the drought level of each month in 20 years to get the approximate drought level of each month.
- The intra- and interspecific interactions of herbs, shrubs, and trees in a plant community can be summarized as the interaction coefficient matrices[10]:

$$R = \begin{bmatrix} 0 & -0.86 & -0.32 & -0.69 \\ 0 & 0.73 & 0.53 & 0.96 \\ 0 & -0.02 & 0.07 & 0.39 \end{bmatrix}, S = \begin{bmatrix} -0.36 & -0.21 & -0.29 & 0 \\ 0.02 & 0.27 & 0.35 & 0 \\ -0.44 & -0.16 & -0.07 & 0 \end{bmatrix}$$

3.1.3 Model Construction

We physically characterize the Drought-Plant Cellular Automaton in following aspects:

- The basic unit of cellular automata is cell (representing a unit of land).
- Each cell memorizes its status (level of vegetation coverage).
- Each cell of the cellular automaton has one state of the four: empty land(0), land with grass(1), land with shrubs(2), land with trees(3).
- For any single cell, its next state is totally determined by the degree of drought and the states of its 8 Moore neighbors (as shown in Figure 2), according to the State Transition Rules.

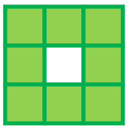


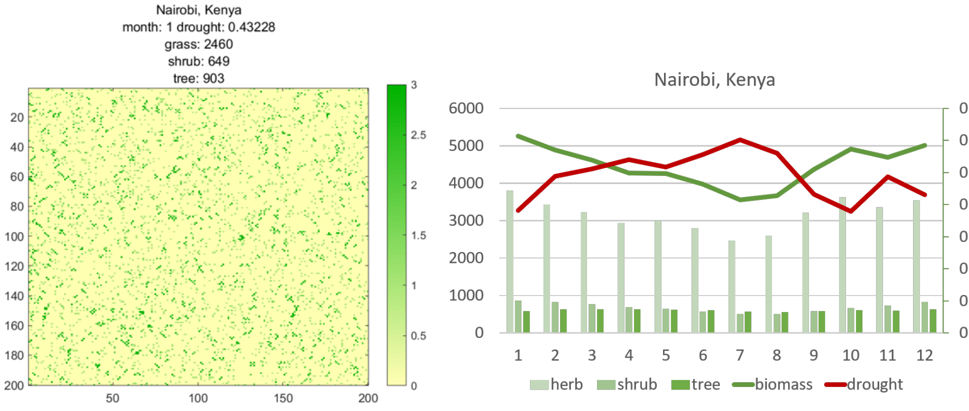
Figure 2: Moore Neighbors(Green) of the White Grid

3.1.4 The State Transition Rules & Algorithm Steps

1. For each month, the primitive drought degree is $d_0 = 0.5 - SPEI/4$, which mostly ranges in $[0, 1]$. And a random fluctuation factor p is generated from $[1-c_{dry}, 1+c_dry]$. The actual drought degree $d = p * d0$.
2. For each month, the vegetation on each unit of land will go through a survival phase and a reproduction phase, and the vegetation will degrade and upgrade according to its survival rate and reproduction rate.
3. For a cell with state x, we say it does not degrade in the survival phase, when its state stays x, otherwise its state degrades to $\max(x-1, 0)$. Similarly, we say it reproduce in the reproduction phase, when its state grows to $\min(x+1, 3)$.
4. For a cell with state x in a month with drought d, assume that there are N_1 herbs, N_2 shrubs, and N_3 trees in its Moore neighborhood, then according to the influence factor matrices S and R, the survival rate of the cell is: $P_s = 1-d+0.1x+\sum_{i=1}^{3} N_i * S_{i,x}$; and the reproduction rate of the cell is $P_r = 0.1 - 0.1 * d + \sum_{i=1}^{3} N_i * R_{i,x}$.
5. Each month for each unit of land we will generate two random numbers i, j uniformly from $[0, 1]$. If $i * p < P_s$, the vegetation survives. If $j * p < P_r$, the vegetation reproduces. By multiplying the fluctuation factor p, we make it harder for plants to survive and reproduce during drought when precipitation should be abundant ($p > 1$), while easier when $p < 1$.

3.2 Result

The result of stimulation is shown in Figure 3-7



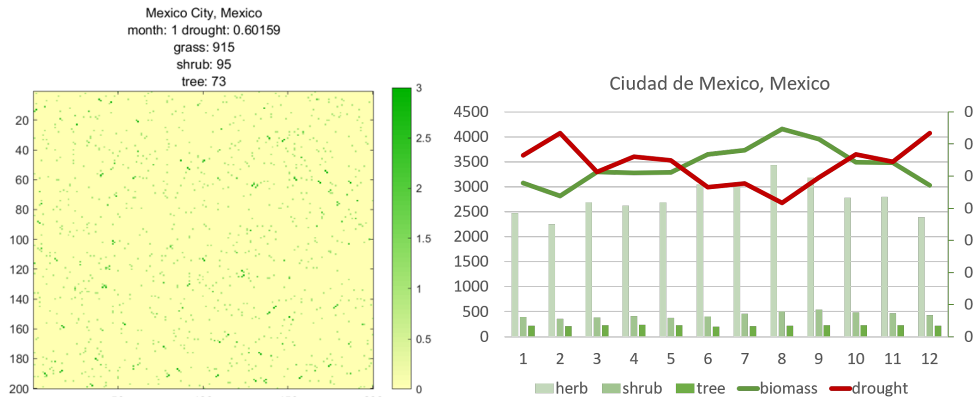
(a) Predicted Vegetation Distribution (b) Monthly Biomass and Drought Degree

Figure 3: Nairobi, Kenya

Analysis of Result

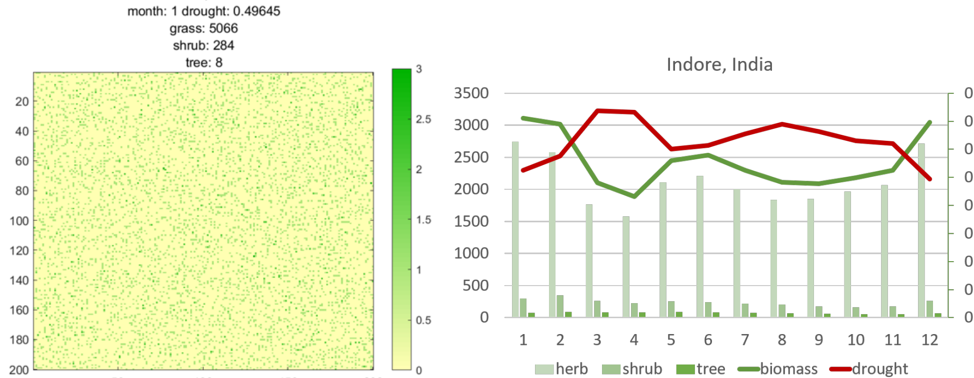
The images on the left visualize the distribution of vegetation in the five regions after the simulation process from January 2001 to December 2020 and count the amount of vegetation in the three categories at the end.

By running the Matlab script and observing the changes of the pictures, we can see that the higher the degree of drought, the lower the overall amount of vegetation. The proportion of the three types of vegetation also varies significantly depending on the weather cycle in different regions. For example, in Indore, which is chronically



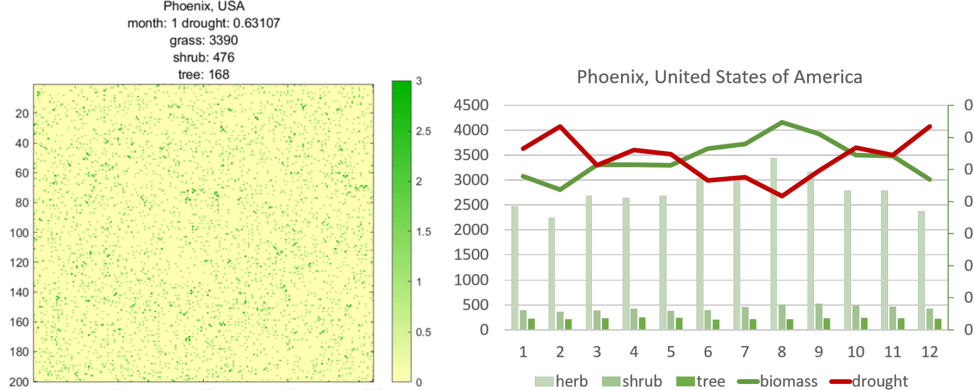
(a) Predicted Vegetation Distribution (b) Monthly Biomass and Drought Degree

Figure 4: Mexico City, Mexico



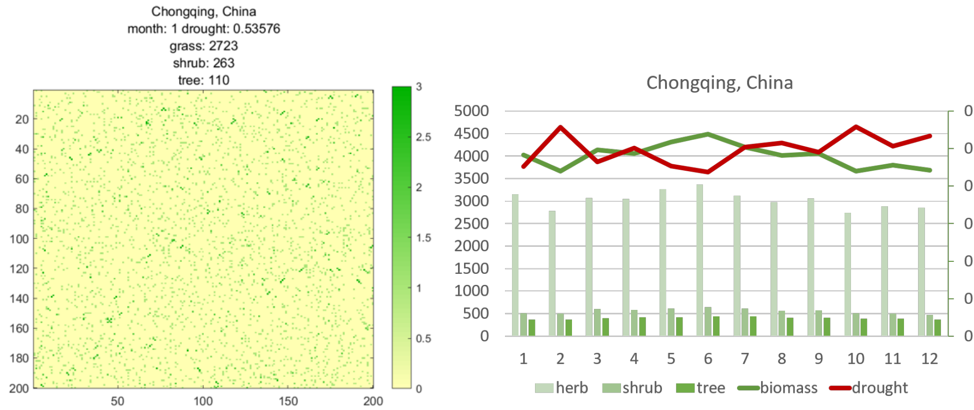
(a) Predicted Vegetation Distribution (b) Monthly Biomass and Drought Degree

Figure 5: Indore, India



(a) Predicted Vegetation Distribution (b) Monthly Biomass and Drought Degree

Figure 6: Phoenix, USA



(a) Predicted Vegetation Distribution (b) Monthly Biomass and Drought Degree

Figure 7: Chongqing, China

dry, the vegetation that grows mainly at the end of the year when the drought level decreases is herbaceous plants that are more resilient; in Nairobi, which is relatively wet throughout the year and has a low drought level in the fourth quarter, a large number of trees can be observed; in Phoenix and Chongqing, the amount of all types of vegetation is maintained at a relatively balanced level.

The graphs on the right side give specific statistics for each month for the three types as well as the overall average biomass (corresponding to the left scale), and the average dryness corresponding to the month (corresponding to the right scale).

By checking the temperature and precipitation data in Figure 3-7, we find that the drought degree in these five regions is intuitively related to temperature and precipitation, but the drought degree in different regions is influenced by these two factors differently due to the geographical locations and climate types differ from each other.

From the plots of overall biomass and drought degree, we can conclude that the survival and reproduction intensity of plant communities are significantly and negatively correlated with the degree of drought, and the longer the drought lasts, the more plants are negatively affected by it (e.g., March and April in Indore). In addition, in the case of paradoxical drought in the rainy season, the reduction of plant community volume will be relatively more due to the fluctuation factor p.

Moreover, in Indore, where aridity is high (above 0.6 almost all year round), the plant community is overwhelmingly herbaceous. According to the paper, we analyzed that this is because herbs have a competitive advantage due to their resilience under prolonged drought conditions, while shrubs and trees have difficulty evolving from herbs and sustaining themselves.

4 The Optimal Species Number Under Various Droughts

4.1 Model Preparation

4.1.1 The Principle of Model

To study the effect of species abundance on plant communities, we conducted separate simulations in two types of areas: moderately dry and more moderate. By reviewing the literature[15, 16], we determined the approximate range of the optimal number of species, and then set scatter points of different species numbers within that range, observed the simulated biomass and other indicators, and selected the value that brought the biomass to near the peak as the optimal number of species.

4.1.2 Model Assumption

- As the number of plant species rises, plant populations become more resistant, but less resilient[15].
- The number of plant species has remained stable and unchanged since it was set. The number of species discussed in the model is the sum of the number of species of all plants and without loss of generality the number of plant species remains stable during the evolutionary process. Model results for different species numbers can be simulated by changing the initial set number of plant species.

- As the number of plant community species is fixed, each type (herb, shrub, tree) has a certain stable proportion of species numbers, otherwise it may lead to the extinction of the community, here only the distribution of species number that can make the population relatively stable is considered.

4.1.3 Refinition of the State Transition Rules

We refined the State Transition Rules in the simulation program to take into account the effect of species numbers on survival and reproduction rates, so that the simulation results reflect the effect of species numbers on the development of plant populations.

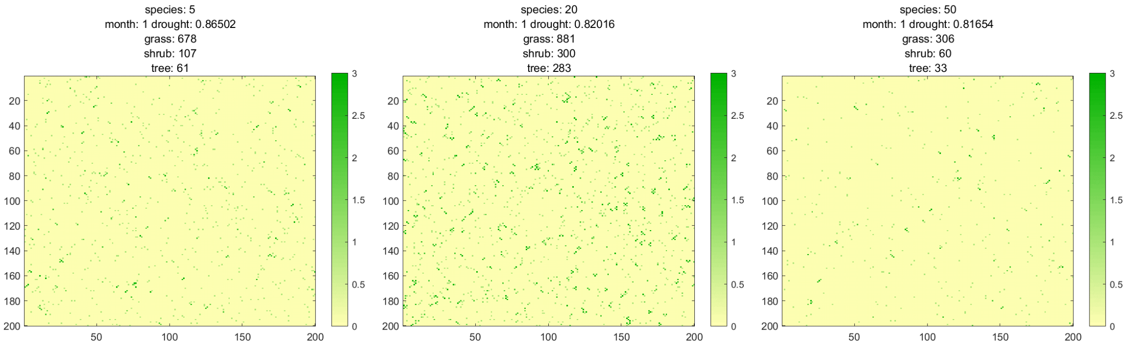
For this model, in a plant community with n species, a cell in state x in a month with drought d, locates in the neighborhood of N_1 herbs, N_2 shrubs, and N_3 trees. The survival rate of the cell is: $P_s = 1 - d + 0.1x + 0.005n + \sum_{i=1}^{3} N_i * S_{i,x}$; and the reproduction rate of the cell is $P_r = 0.1 - 0.1 * d - 0.001n + \sum_{i=1}^{3} N_i * R_{i,x}$.

4.2 Result in Moderately Dry Regions

We selected Mexico City as a moderate drought experimental area and conducted three sets of tests under controlled variables under the environmental conditions shown in the Figure 8, corresponding to 5, 20 and 50 species.

Observing the vegetation distribution map as well as the plot graph of monthly total biomass, we can see that the plant community has the largest volume when the number of species is 20. We analyze the reasons which may be that when the number of species is too small, the resistance of the community is weak, and the community volume decreases rapidly when the drought level is high, while when the number of species is too large, the recovery of the plant community is weak, and it is difficult to recover to the original volume quickly after the drought.[9]

Moreover, the trend of the curve in Figure 8 can illustrate this point well: as the number of species increases, the less the total biomass varies between months, i.e., the more stable the community's body mass is. When the number of species in the community is large, the community is resistant and climatic fluctuations within a reasonable range have less effect on the total biomass, thus the flatter the curve.



(a) Species = 5 (b) Species = 20 (c) Species = 50

Figure 8: Predicted Distribution of Different Species Numbers in Mexico City

Based on the graph we conclude that for a moderately arid region such as Mexico City, the number of species suitable for plant community development is around 20.

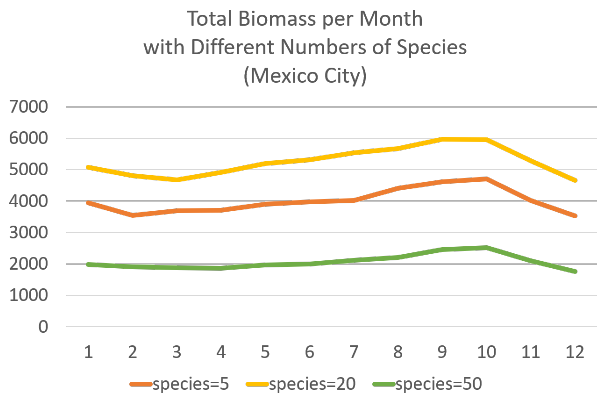
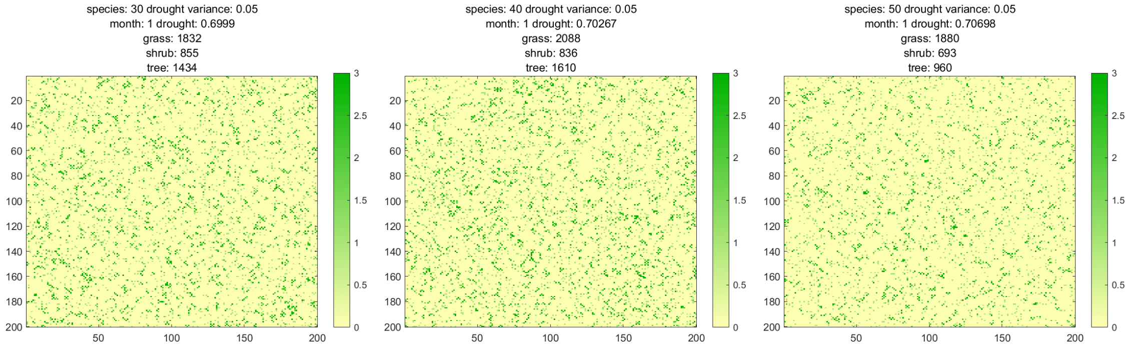


Figure 9: Predicted Monthly Biomass Plot of Different Species Numbers in Mexico City

4.3 Result in Mild Dry Regions

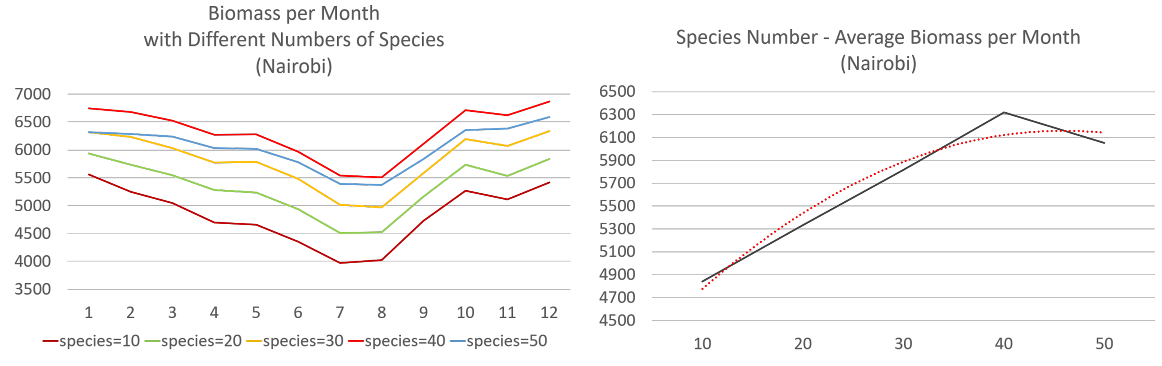
We chose Nairobi as the experimental area in the mildly arid region. To investigate the optimal number of species in the mildly arid region, we used the gradient experiment method and set up 5 simulations with a gradient of 10, to observe their vegetation distribution and biomass statistics.

The figure below shows the distribution of vegetation at species numbers of 30, 40, and 50, respectively, and the biomass statistics in all experiments. It was observed that the community volume peaked when the number of species was around 40.



(a) Species = 30 (b) Species = 40 (c) Species = 50

Figure 10: Predicted Distribution of Different Species Numbers in Nairobi



(a) Predicted Biomass Plot of Different Species Numbers (b) Average Biomass-Species Number Plot

Figure 11: Predicted Biomass of Different Species Numbers in Nairobi

In Figure 11(b) we trace the mean values for each month of the year in different experiments, followed by a polynomial curve fit, and find that the curve peaked roughly at a species number of 45.

This gives us the result that the optimal number of species is 45 in the mildly arid region such as Nairobi. This peak has a large positive shift compared to the moderately arid region. We analyzed the survival and reproduction rates affected by species numbers in the model and found that species reproduction levels were already at high levels under mild drought conditions, and that the increase in survival rates due to higher species numbers had more significant benefits for community size under increased environmental capacity.

5 The Impact of Species Type and Drought Fluctuation on Plant Community

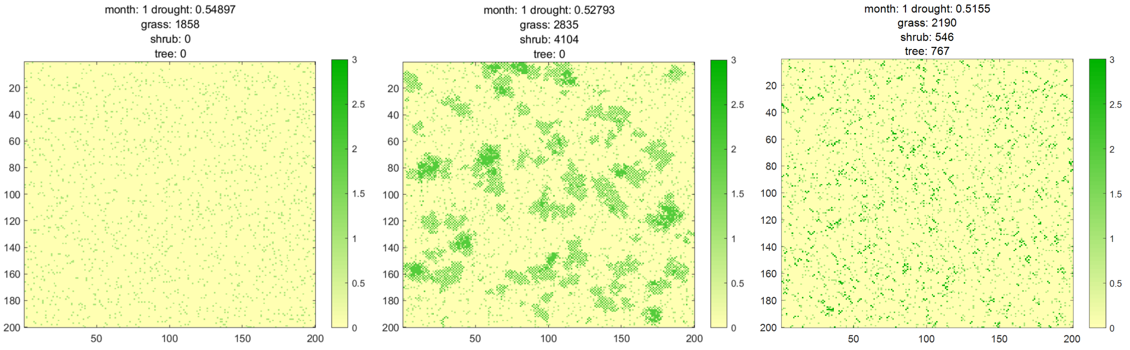
5.1 Analysis of the Two Factors

Because there are large differences in the extent to which different types of plant species are affected by drought fluctuations, we discuss the effects of drought fluctuations and species types on plant communities in this section.

5.2 The Impact of Species Type on Plant Community

To study the effect of species type on plant communities, we changed the upper limit of the vegetation coverage levels in the reproduction process in Drought-Plant Cellular Automaton.

For example, by setting the upper limit to 2, we can simulate the change of plant communities in temperate grasslands where only herbs and shrubs grow. By setting the upper limit to 1, we can simulate the situation of herbaceous plant community only in high altitude environment.



(a) Herb-only (b) Herb and Shrub (c) Herb, Shrub and Tree

Figure 12: Predicted Distribution of Different Types Numbers in Nairobi

With three sets of simulation experiments, we obtained the results in Figure 14 From the changes in the simulated plant distribution maps, we learned that under the drought conditions in Nairobi, the herbaceous-only community was very unstable and the community volume fluctuated greatly with the degree of drought: it died out rapidly in drought and recovered rapidly in wet conditions; after adding shrub species to the ecosystem, there was a significant increase in the stability of the plant community, and shrub individuals gathered to form stable patches, and this community's The biomass of this community was also the highest; while the biomass of the community

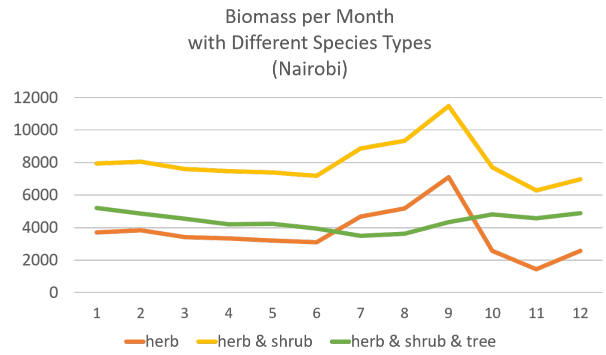


Figure 13: Predicted Monthly Biomass Plot of Different Species Types in Nairobi

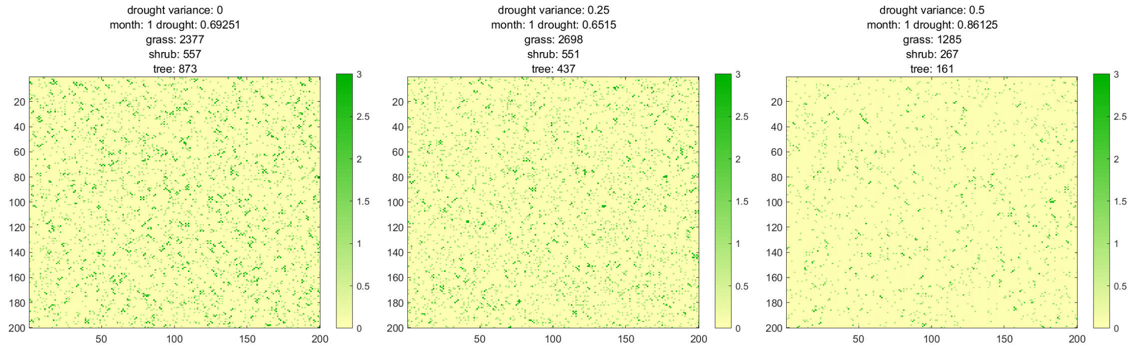
decreased after the addition of trees, but the biomass became significantly flatter with the change of months.

This shows that shrubs and trees have an important role in the resistance (stability) of the plant community.

5.3 The Impact of Drought Fluctuation on Plant Community

For the simulation of drought fluctuations, we adjust c_{dry} to make the actual drought level differ from the original data, a larger c_{dry} will lead to larger drought fluctuations.

By comparing the variance of drought degree, we set the experimental site in Nairobi, where the drought degree is more variable, and set c_dry to 0,0.25,0.5 for three sets of control variable experiments, respectively.We obtained the following experimental results:

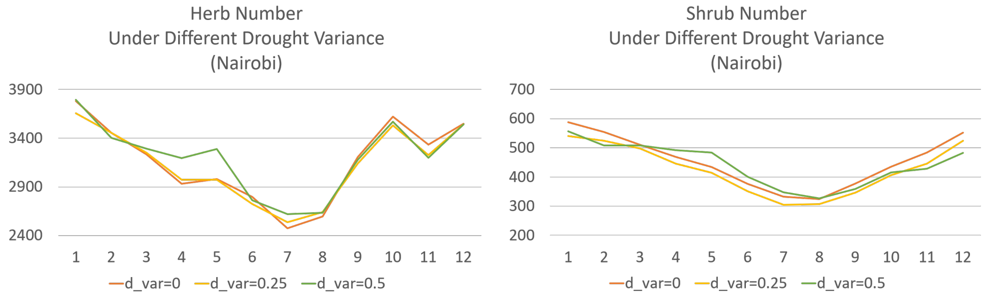


(a) Stable Drought (b) Fluctuated Drought (c) Extremely Volatile Drought

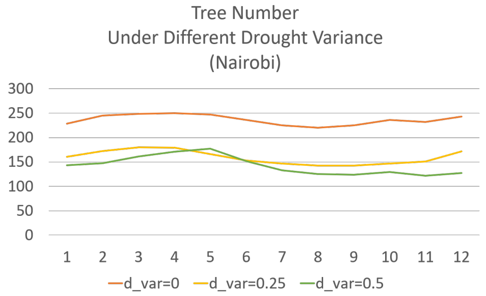
Figure 14: Predicted Distribution with Different Drought Variance in Nairobi

After the experiments, we obtained the results shown in Figure 14 . From the vegetation distribution, we find that when the plant community faces a certain degree of drought fluctuation, the proportion of herbs increases and the proportion of shrubs and trees decreases in relatively stable drought, and the number of herbs decreases significantly in the case of great fluctuation.

This is because herbs are more resilient when there are frequent drought fluctuations and thus can still recover their numbers quickly after being subjected to large excursions in a single month, but shrubs and trees are unable to recover and lead to a decrease in their share. From the biomass plots, we can also observe that the most affected by drought fluctuations are the trees, followed by shrubs, and the least by the herbs.



(a) Stable Drought (b) Fluctuated Drought



(c) Extremely Volatile Drought

Figure 15: Predicted Distribution with Different Drought Variance in Nairobi

6 The Impact of Other Factors on Plant Community

6.1 The Impact of Fire on Plant Community

We simulated the spread of fire in the plant community by adding a state to the cell (with -1 for fire). To do so, we added rules for the generation, extinction, and spread of fire to the State Transition Rules.

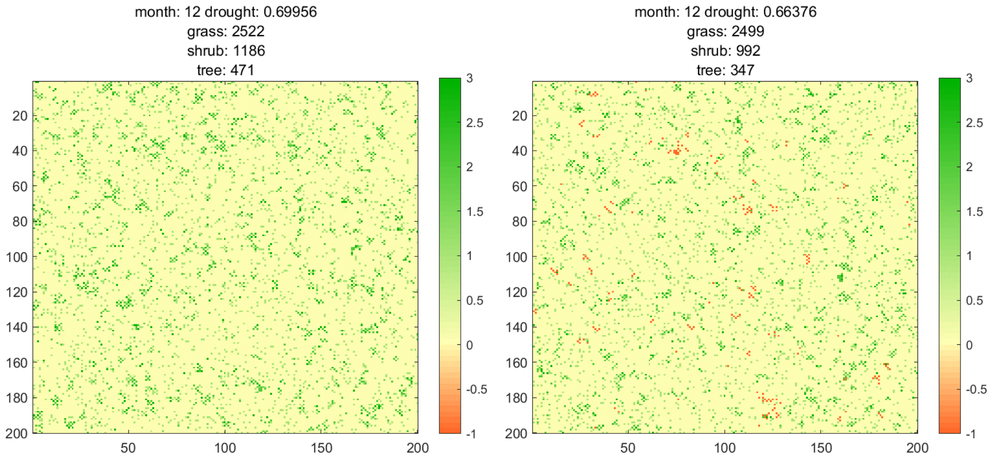
The Generation and Spread of Fire:

The occurrence of fire in nature is usually correlated with the degree of drought, and the greater the dryness, the greater the probability of spontaneous combustion of plants leading to fire. Therefore, for each monthly iteration, we calculate the probability of fire initiation for each unit of land with vegetation cover to decide whether to start a fire or not.

In a month with drought degree d, for a land covered by some vegetation, with x units of fire in its Moore neighborhood, the probability for the plant to burn is $P_b = 0.001\text{d}+0.5x$.

The Extinction of Fire:

We took advantage of the "reproduction rate" P_r in the model: since fire is -1, its extinction can be simulated as adding a level of vegetation coverage. We set the probability of extinguishing a land fire to be $P_r = (1-d) * 0.1$. That is, the lower the drought level, the higher the probability of fire suppression.



(a) Without Fire (b) With Fire

Figure 16: Predicted Distribution Considering Fire in Nairobi

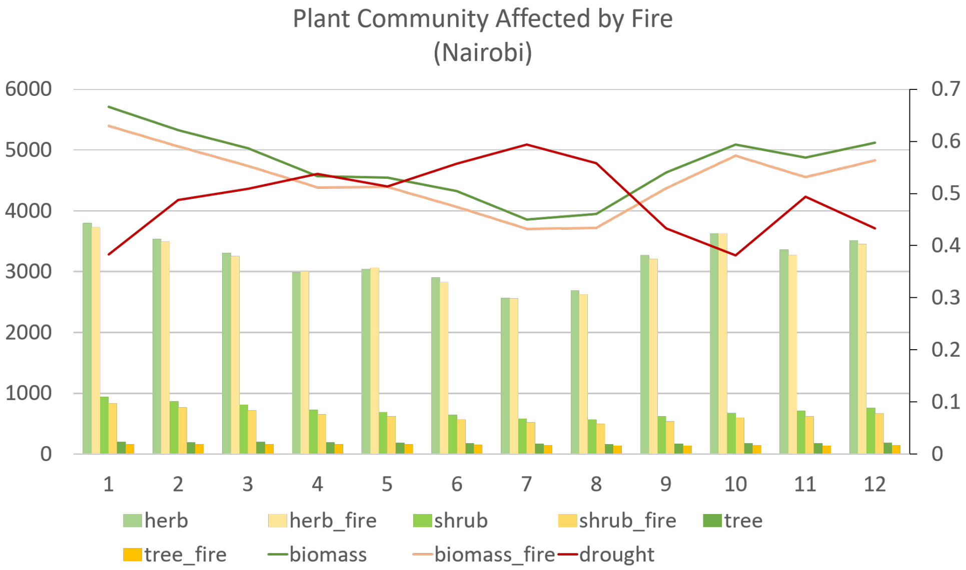


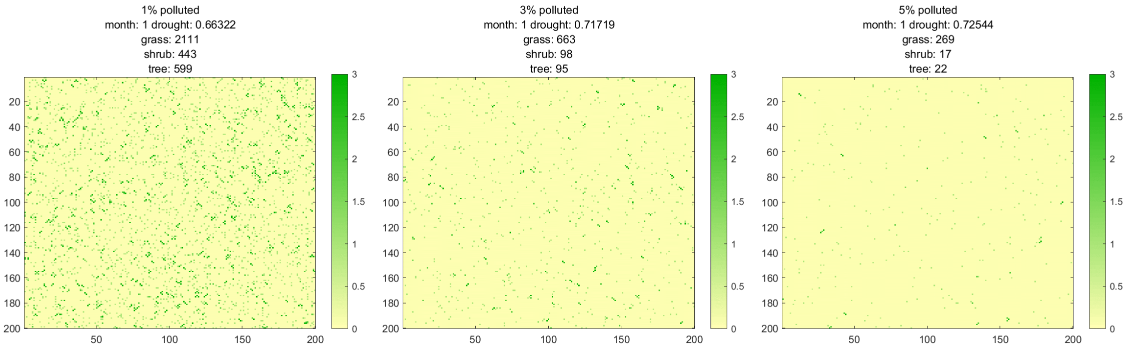
Figure 17: Predicted Monthly Biomass Affected by Fire in Nairobi

After taking fire into account for the simulation experiment, we compared the data with the data without fire, and the results are shown in Figure 17.

We found that fire had some reduction effect on all three types of vegetation, and that trees had the largest percentage reduction and herbs the smallest because of fire. The reason for this analysis may be that herbaceous plants can recover quickly after fire and the proportion affected by fire can be replenished within a few months. Nevertheless, as shown in the line graph, fire had a significant effect on the overall biomass for each month.

6.2 The Impact of Pollution on Plant Community

With the development of human civilization, the pollution has become an important factor affecting the changes in plant communities. For one thing, environmental pollution decreases the survival and reproduction rate of plants (e.g., heavy metals from industrial emissions). For another, it also makes the habitat for plant survival diminish, which will be discussed in the next subsection.



(a) Slightly Polluted (b) Moderately Polluted (c) Severely Polluted

Figure 18: Predicted Distribution Under Different Levels of Pollution

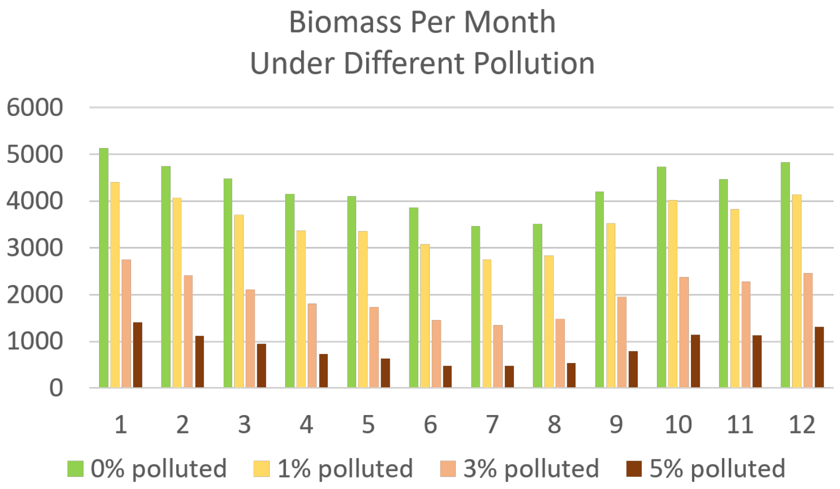


Figure 19: Predicted Monthly Biomass Under Different Levels of Pollution

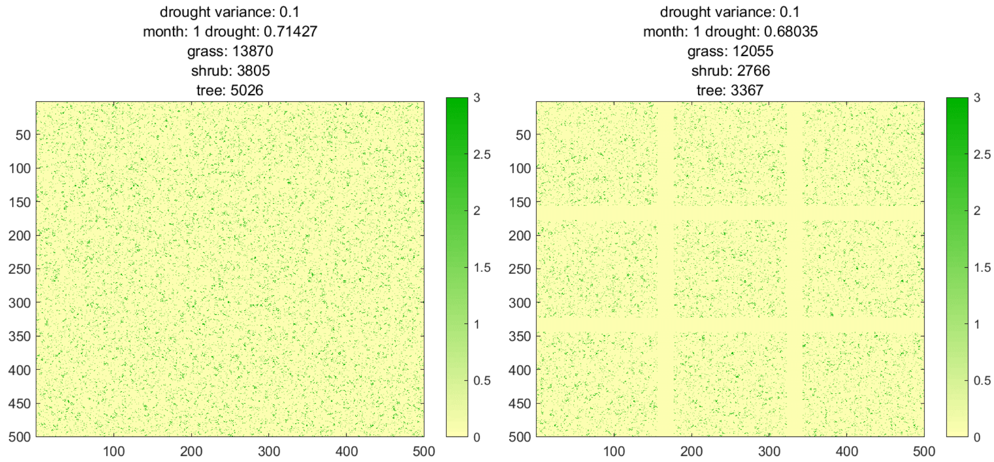
For the simulation of pollution, we adjusted the survival and reproduction rates of plants downward accordingly according to the degree of pollution and obtained the changes of plant communities with reduced survivability.

It can be intuitively seen from the vegetation distribution map that the pollution degree has a great impact on the plant community size. It can also be seen from the bar chart that the negative impact of pollution degree on the community biomass is non-linear, and a small impact on the survival rate and reproduction rate can lead to a huge loss of biomass.

6.3 The Impact of Habitat Reduction on Plant Community

The habitat of plant communities is also challenged in many ways: human exploitation of land and irreversible habitat loss due to desertification. In this section, we simulate the construction of four roads in an undeveloped area of 500*500. The developed roads will not be able to grow vegetation, as shown in Figure 20.

Intuitively, as plants have less space to grow, their biomass naturally decreases. But given that four roads divided the formerly connected areas into nine uncommunicated ones, the community became more unstable and the biomass it produced per unit area decreased.

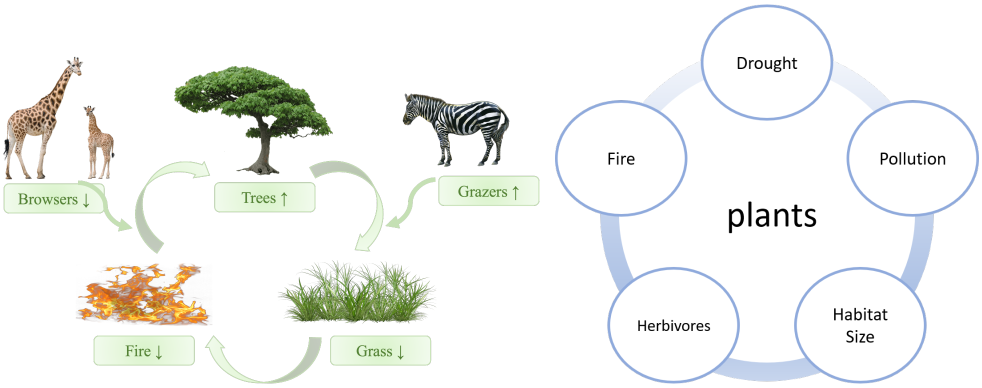


(a) Without Habitat Reduction (b) With Roads Construction

Figure 20: Predicted Distribution Considering Habitat Reduction in Undeveloped Areas

6.4 Additional Details

Grass - fire - Herbivore - tree positive feedback(Figure.21). Compared with the influence of environment on plants, the interaction mechanism of environment to environment is more complex. Interactions such as fire, herbivores, and plants are a positive feedback effect: herbivores reduce the amount of grass, and leaf-eaters reduce the amount of shrubs and trees. And reducing grass can reduce the content of fuel, reduce the fire, further promote the growth of trees, inhibit the growth of grass; Fewer trees can encourage grass growth and cause fires that further inhibit tree growth, Promote the growth of grass[17]. Other factors affecting fire include species richness, species characteristics and season of fire.



(a) Grass-fire-herbivore-tree positive feedback (b) natural disturbances

Figure 21: Additional Details

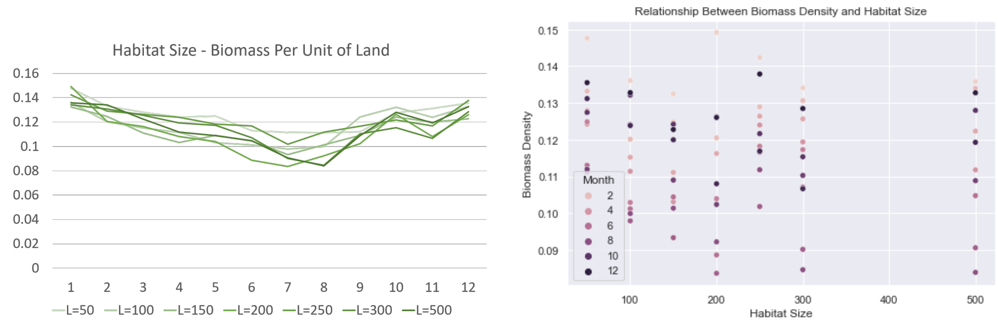
Effects of soil pollution on grassland community composition. Taking the African steppe community as an example, the main pollution is soil pollution and groundwater pollution caused by mining. These pollutants affect the soil microbial community and other ways to make the grassland soil conditions more barren, the community competition pressure is greater, and the total biomass decreases[20]. herbs have developed root system, however, The biomass of trees and shrubs decreased while that of grasses increased. Therefore, the biomass of trees and shrubs decreased while that of grasses increased. The composition of grassland communities has also changed.

Habitat loss. In addition to the direct effect of habitat area reduction on the total biomass of plant community, habitat reduction also has a great effect on the biomass per unit area of the community[18]. The decrease of habitat area makes the distribution of habitat tend to be fragmented, thus affecting the pollination and seed retransmission of plants located at the edge of habitat, and thereby reducing the reproduction rate of plants. In addition, habitat fragmentation means that the spatial distance between plant communities and unnatural disturbances is closer, which makes plants more susceptible to various unnatural disturbances and decreases their survival rate. The decrease of reproduction rate and survival rate resulted in the decrease of biomass per unit area.

7 Sensitivity Analysis

Through the above analysis, we obtained a model that can predict the changes of plant communities under different factors such as drought conditions, species type and number of species. At the same time, many parameters are introduced into our model. In order to ensure the robustness of the model, we tested the model from the following aspects.

First, to ensure that the model can be applied to land of different sizes, we adjusted the habitat size L with a gradient of 50, and counted the biomass on a unit land of the corresponding plant community, as shown in Figure 22. It can be found that the fluctuation of biomass on unit land is mainly caused by the fluctuation of drought degree, and there is no obvious correlation with habitat size. Therefore, our model has weak correlation with habitat size, and can be generally adapted to the changes of plant communities on land of various sizes.



(a) Habitat Size - Biomass per Unit Land Plot

(b) Scatter plot of biomass per unit of land and habitat size

Figure 22: Sensitive Analysis of Habitat Size L

Moreover, our model design allows us to change the parameters shown below. Next we develop a detailed analysis of following paramters' impacts on the model.

We record the values of the annual cumulative biomass M_c – the sum of biomass for a total year – in each case with changes of 10%, 5%, -5%, and -10%. And the table 3 has shown how the values of M_c change as the parameters fluctuates.

According the above data, we can see these parameters' impact extend on the stability.

The results of initial biomass M_{init} analysis show that it has no significant effect on annual cumulative biomass 20 years later in the range of -10%-10%. When the number of iterations reaches 240, the distribution of vegetation usually reaches the environmental capacity, while the difference caused by the initial biomass in the early

Table 3: Results of Sensitivity Analysis

	-10%	-5%	0%	5%	10%
M_{init}	52649.4	52832.75	52914.2	53427.78	53398.85
P_s	42103.73	46533.08	52914.2	60576.78	68788.35
P_r	47597.38	50436.68	52914.2	56212.38	60102.7
P_b	51856.13	51256.13	49905.38	48774.88	47469.08

equilibrium is gradually weakened, so its influence on the annual cumulative biomass is not obvious.

The results of sensitivity analysis of plant survival rate P_s and reproduction rate P_r showed that the plant survival rate and reproduction rate would have a great influence on the annual cumulative biomass in the simulation process within the range of ±10%. In this model, the volume of the plant community is directly determined by these two factors, so the cumulative biomass throughout the year is highly sensitive to their changes.

8 Strengths and Weaknesses

8.1 Strengths

- Our model realizes the visualization of plant community evolution through MATLAB program, which can make people more intuitive observation and understanding of community changes compared with pure formula derivation, and has a good agreement with the actual situation.
- With various reliable theoretical basis, considering sufficient factors and cases, and reasonable simplifications, we build the Drought-Plant Cellular Automaton Model to solve the problems. The results are consistent with both theoretical data and actual practice, and have high credibility.
- We set our model in some regions with typical climate features around the world. Therefore, our model is very scalable and can be applied to different regions around the world with only a few simple modifications of parameters
- Our data sources are reliable and abundant, which effectively avoids the negative impact of data deviation or error on the model and ensures the effectiveness and accuracy of the model.
- The sensitivity analysis of the model shows that the parameter settings are reasonable.

8.2 Weaknesses

- Although many factors are considered in this paper, some factors that may affect plant community changes (such as large-scale natural disasters) are still excluded from the hypothesis, so the simulated situation of the model may be different from the actual situation.
- In reality, the model's assumptions don't always hold true. So there may be cases

that violate our model.

8.3 Promotion

- Select more areas for sampling, use a wider range of meteorological data to adjust the parameters, so that the model has a higher credibility and universality.
- Optimize the efficiency and interface of the visualization program to make the model more intuitive, beautiful and easy to understand, etc.

9 Strategies to Ensure Long-term Viability of Plant Communities

- When abnormal climate occurs, especially when drought frequency is high or drought time is abnormal, artificial rainfall and other measures can be used to reduce drought index and help maintain community stability.
- Supplement species for unstable plant communities to the optimum number of that location, which can be derived from the above model, to enhance its stability in the face of natural disturbances.
- In the work related to arid areas, such as restoring grassland ecosystems, priority should be given to the planting of adaptable plant types, such as shrubs and grasses, so that the plant community can develop in a more stable trend.
- Pay attention to grassland fire prevention, through the manufacture of isolation belts, to minimize fire losses; Focus on reducing pollution, especially soil pollution, and try to avoid practices such as open-pit mining; When carrying out human activities in the wild, such as building infrastructure, try to avoid dividing habitats.

10 Conclusion

Based on the cellular simulation results, we found that the interaction between species plays an important role in the resistance of plant communities to natural disturbances such as drought. The model provides detailed answers to the required questions.

Firstly, the changes of grass, shrub and tree biomass in five regions within a year showed that the biomass of all three types of plants was negatively correlated with the drought index, and drought under variable and abnormal conditions (drought when it should be wet) had a greater negative impact on the community. Among the three plant types, the variation amplitude was grass > shrub > tree.

Secondly, the role of species richness in plant community resistance to drought changes with the number of species. When the number of species is low, the community resistance to drought increases with the number of species. The drought resistance of the community decreased with the increase of the number of species. The average monthly biomass reached its maximum level when the number of species was about 20.

Thirdly, the effects of species richness on the drought resistance of plant communities changed when the fluctuation amplitude and frequency of drought intensity changed. When the fluctuation of drought degree decreases and the occurrence frequency decreases, the competition between species decreases and the number of optimal species increases to 45.

Finally, fire, pollution, habitat reduction and other factors had negative effects on the biomass of plant communities to varying degrees. Fires and large herbivores had the greatest impact. The biomass of shrubs and trees of the three plant types was consistently negatively affected, while grass, due to its strong competitive advantage, was least affected and even increased in a few months

Appendix: Our Code

```
clear;clc; load('land_color_map.mat'); load('drought_data.mat'); L = 200;T = 240;Sd = zeros (L+2);region=1;month=0; pollute=0; land=arrayfun(@generate,rand(L));

Sd(2:L+1,2:L+1)=land; veg=zeros(3,L,L); total=zeros(12,5); biomass=[1,1.5,2.5]; d_var=0.1; cnt=1; while(cnt<=T) d=0.5-dry(cnt,region)/4; dry_coe=((1-d_var/2)+d_var*rand()); d=d*dry_coe; total(month+1,5)=total(month+1,5)+d; Sd(2:L+1,2:L+1)=land; veg=zeros(3,L,L); for i=2:L+1 for j=2:L+1 for p=-1:1 for q=-1:1 if(p*q =0 && Sd(i+p,j+q) =0) veg(Sd(i+p,j+q),i-1,j-1)=veg(Sd(i+p,j+q),i-1,j-1)+1; end end end end end for i=1:L for j=1:L

[surv,repro]=calc_rate(d,land(i,j),veg(1,i,j),veg(2,i,j),veg(3,i,j));

if(rand()*dry_coe>=surv&&land(i,j)>0) land(i,j)=land(i,j)-1; end

if(rand()*dry_coe<repro&&land(i,j)<3) land(i,j)=land(i,j)+1; end end end

veg_cnt=count_veg(land,L); for i=1:3 total(month+1,i)=total(month+1,i)+veg_cnt(i); end colormap(land_color_map);image(land,'CDataMapping','scaled'); title({['drought variance: ',num2str(d_var)],['month: ',num2str(month+1),' drought: ',num2str(d)],['grass: ',num2str(veg_cnt(1))],['shrub: ',num2str(veg_cnt(2))],['tree: ',num2str(veg_cnt(3))]}); colorbar; clim("manual"); set(gca,'CLim',[0,3]);pause(0.001); month=mod(month+1,12); cnt=cnt+1; end for i=1:12 for j=1:5 total(i,j)=total(i,j)/20; end total(i,4)=total(i,1)*biomass(1) +total(i,2)*biomass(2)+total(i,3)*biomass(3); end function type = generate(x) p_veg = [0.3,0.1,0.002];if(x<=p_veg(1)) type=1; elseif(x<=p_veg(1)+p_veg(2)) type=2;

elseif(x<=p_veg(1)+p_veg(2)+p_veg(3)) type=3; else type=0; end end function [veg] = count_veg(land,L) veg=[0,0,0]; for i=1:L for j=1:L if(land(i,j) =0) veg(land(i,j))=veg(land(i,j))+1; end end end end function [survival,repro]=calc_rate(d,x,grass,shrub,tree) species=0; if(x>=0) ic_surv=[0,-0.86,-0.32,-0.69;0,0.73,0.53,0.96;0,-0.02,0.07,0.39]; ic_repro=[-0.36,-0.21,-0.29,0;0.02,0.27,0.35,0;-0.44,-0.16,-0.07,0]; base_surv=1-d+0.1*x; base_repro=0.1-0.1*d; survival=min(base_surv+(ic_surv(1,x+1)*grass+ic_surv(2,x+1)*shrub+ic_surv(3,x+1)*tree) +0.005*species,0.99); repro=base_repro+(ic_repro(1,x+1)*grass+ic_repro(2,x+1)*shrub

+ic_repro(3,x+1)*tree)-0.001*species; else survival=0; repro=(1-d)*0.1;end end function fire_rate=burn(d,x,fire) if(x>0) fire_rate=0.001*d+fire*0.5; else fire_rate=0;end end
```

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