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Jinjin He
Changwen Zeng
Quanshen Shen

With Student Advisor

Jinjin He

Of

Huazhong University of Science and Technology

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Kelly Black

Kelly Black, Head Judge

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Simulation and Modeling of Diverse Fungal Colony

Summary

In this paper, we researched the effects of fungal growth rate and moisture tolerance on the rate of fungal organic matter consumption, and studied the interactions between fungi mixed in different environmental factors and their respective advantages, and finally discussed the importance of biodiversity through our multi-fungal model.

In order to analyze the change in the population of a fungus, we derived the relationship between the number of fungal populations and time using the Gomperzt model. At the same time, we obtained empirical equations for organic matter decomposition rate and growth rate and moisture tolerance of fungal populations through rational analysis and numerical simulation, and added them to the Gomperzt model to obtain the relationship of the two traits of interest, growth rate and moisture tolerance, with the rate of decomposition. After considering the effect of temperature and moisture on the fungus, we introduced active factor to quantify the effect of temperature and moisture on various aspects of the fungus.

After analyzing one fungus, we used cellular automata to model the interactions between multiple fungi. For different fungi, we used optimum temperature interval, optimum moisture interval, growth rate and moisture tolerance to differentiate them. Also, to distinguish the environments, we used temperature, moisture and organic matter production rate to describe the different environments.

In different environments, we set four different fungi for simulation and obtained a plot of fungal organic matter decomposition versus time for each case. After long-term and short-term analysis in each of the five regions, we came to some conclusions, such as: in the case of abundant natural resources and small range of temperature and moisture variation, after a longer period of time, the fungal species with big range of growth rate and moisture tolerance are more viable; in the case of restricted resources and greater temperature and moisture variation, after a longer period of time, the strains with smaller growth rate and moisture tolerance had better survival ability.

After that, we compared the organic matter decomposition rate of the multifungal model and the Single fungal model, and considered the effect of temperature change on the organic matter decomposition rate of fungal communities with different biodiversity in a certain area, and plotted the organic matter decomposition rate and its relative change rate at different temperatures, and concluded that biodiversity can improve the cycling efficiency and stability of the ecosystem.

After that, we considered the sensitivity of the initial fungal population and the amount of organics production per unit time on the amount of organic matter decomposition after stabilization, and analyzed the advantages and disadvantages of the model.

Finally, we synthesized the conclusions we had obtained and wrote an article about the roles fungi play in ecological systems for college level biology textbook.

Contents

1 Introduction

1.1 Problem Background

The carbon cycle plays a very important role in ecosystems, and one of the important processes is the decomposition of organic matter by microorganisms to release carbon dioxide back to the atmosphere, and saprophytic fungi are important members of this process. The most recent study of growth rate and moisture tolerance are related to these two important characteristics. Since we can measure the organic matter decomposition efficiency of saprophytic fungi to reflect the carbon cycle rate of an ecosystem, we can explore the relationship between the growth rate and moisture tolerance of fungi and draw some conclusions about the ecosystem.

1.2 Analysis of the Problem

This problem gives some relationships between fungal organic matter consumption and its mycelial growth rate and moisture tolerance in a qualitative and semi-quantitative way, and briefly describes the qualitative connections between some state parameters during fungal growth. On this basis, we were asked to explore the relationship of the two traits of interest, growth rate and moisture tolerance, with the rate of decomposition, and we were also asked to give some simulations of colony growth processes in nature, to analyze the relationships between multiple fungi, and to analyze the importance of fungal biodiversity.

This leads to some questions.

1. How to quantify the relationship of the two traits of interest, growth rate and moisture tolerance, of a single species of fungi in organic matter decomposition process, with the rate of decomposition?
2. In the case of multiple fungal interactions in nature, how can these interactions be described? And what effect do these interactions, in turn, have on the outcome?
3. In addition to this, how do the above results change in different scenarios, taking into account changes in ambient temperature and moisture?
4. Based on the above results, what are the advantages and disadvantages of fungi with different growth rate and moisture tolerance in different environments?
5. What is the importance of biodiversity in the analysis of the advantages of mixed colonies over single colonies in the environment?

2 Preparation of the Models

2.1 Assumptions

- **Assumpions 1**: We only consider saprophytic fungi (i.e., saprophytic objects can be considered as woody fibers), and the organic matter in this paper is also the saprophytic object

$\hookrightarrow$ **justification**: In this problem, we mainly research the proliferation process of different fungal species and the interaction between them, so in order to simplify the model, we do not need to consider the effects caused by different saprophytic objects.

- **Assumpions 2**: When considering environmental factors, only temperature and moisture and organics will affect the colonies, and we do not consider the effects of extreme environmental factors (fire, tornado, etc.) on our model.

  $\hookrightarrow$ **justification**: Natural environmental effects include precipitation, light and temperature, where precipitation can be measured by moisture, while light and temperature can be measured by temperature, and the amount of organics mass will also be considered. At the same time, biological active factor is not predictable in extreme environments, so it is not considered.

- **Assumpions 3**: In this problem, all the fungi we discuss cover the surface of the saprophytic object uniformly.

  $\hookrightarrow$ **justification**: In nature, most fungi grow on the surface of saprophytic objects. For the same class of fungi, in order to avoid individual differences, we estimate the results of overall statistical benefits by replacing the average unit surface density.

- **Assumpions 4**: In the initial Gompertz model, only single species of fungi were considered.

  $\hookrightarrow$ **justification**: In the early stage of fungal colony development, the mixed situation of different kinds of fungi is relatively less. We will elaborate later on in the mixed fungi model.

- **Assumpions 5**: The rate of organic matter accumulation is only related to different regions and seasons. In the short-term model, the temperature and moisture were constant; in the long-term model, the temperature and moisture varied through the change of seasons.

  $\hookrightarrow$ **justification**: The organic matter accumulation rate in a certain region is not strictly equal at the same time though, and considering the need to draw statistical conclusions, we substitute the mean value.

2.2 Notations

The primary notations used in this paper are listed in Table 2.

Table 1: Notations

Symbol	Definition
b	The initial growth rate of the fungi
$S(t)$	Area of the fungi
k	Constant to describe fungal growth rate in relation to area
v_h	Hyphal extension rate
T	Temperature
M	Moisture

t	Time
T_0	Optimum temperature of fungi
T_1	The temperature width of the fungi
M_0	Optimum moisture of fungi
M_1	The moisture width of the fungi
P_{v_h}	Probability of fungal transmission to the surrounding area
P_o	Rate of Organics
Nf	Ratio of initial Organics
v_c	Percentage of organic matter consumed per unit time
P_{v_c}	Proportion of organic consumed by fungi per round
mt	Moisture tolerance

3 Growth Model of a Single Fungi

3.1 Gompertz Model

To depict the specific growth of fungi in wood, we took the **Gompertz model**[2]. This model depicts the growth of microorganisms with environmental constraints. When the survival of the microorganism is not constrained, the rate of increase of the organism is proportional to its number, but the number increases to a certain level when it is constrained by the environment and the growth rate decreases.

$$N(t) = N_0 \exp(\ln(\frac{N_I}{N_0}))(1 - \mathrm{e}^{-bt}) \tag{1}$$

Where N_I is the maximum environmental capacity, this parameter is related to the specific fungal species, and the characteristics of the environment. N_0 is the initial number of fungi, and b is the initial growth rate of the fungi.The initial growth rate of the fungi has a wide range of variation. We assume that the number of fungi per unit area is certain, so that we can exchange the number of fungi for the area of fungi.

$$S(t) = S_0 \exp(\ln(\frac{S_I}{S_0}))(1 - \mathrm{e}^{-bt}) \tag{2}$$

S_0 is the initial colony area. S_I is the maximum colony area. In our model, because the colony area and sample area are certain, these two values are set as a constant. $S_0 = 1mm \times 1mm$,$S_I = 10mm \times 10mm$.

3.2 The Influences of Hyphal Extension Rate and Moisture Tolerance

As the wood corrosion rate and area is positively correlated, but because the corrosion rat(α) of the area has been covered by the fungi for a long time than just contact with the fungi area corrosion rate is low, α should be less than 1, and if we only consider the area edge fungal corrosion, then α is 0.5. Therefore, 0.5 < α < 1.

Based on the curve results of previous studies[5], we believe that 0.5 <α < 1 are desirable, in the article we can take α for 0.75 as a reference. The equation shows that the rate of wood corrosion is proportional to the number of fungi per unit area. v_c is the overall consumption rate of the entire wood.

$$v_c = f(mt)S(t)^{\alpha} \qquad (0.5 < \alpha < 1) \tag{3}$$

From the relationship between mt and wood corrosion rate in the paper[1], we can get the relationship equation of fungal corrosion rate.

$$f(mt) = k\mathrm{e}^{(0.85mt+1.85)} \tag{4}$$

k is a constant for all colonies which is related to S_I. This is because when we examine the same temperature, the maximum difference in the rate of corrosion of wood by fungi with the same growth rate is consistent with the curve of moisture tolerance. We obtained the value of k by fitting the curve.

In the numerical calculation in Figure 1, the relationship between b and hyphal extension rate is $b = 0.04\ v_h$

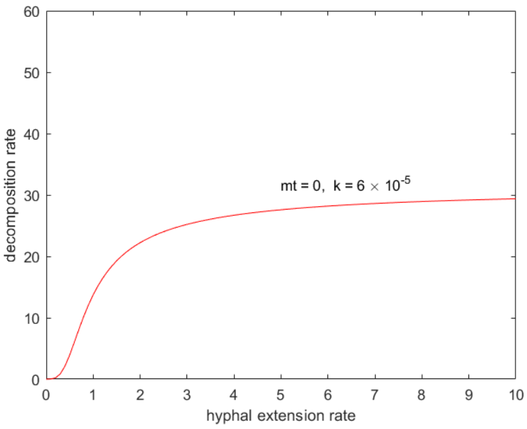


Figure 1: The relationship between the hyphal extension rate and decomposition

In order to express the corrosion rate of wood, we adopt the method of integration of the corrosion rate to calculate.

$$\int_0^t v_c\, dt = D_r \tag{5}$$

Dr is the decomposition rate ,t is the time of fungi corroding wood .In our model, t is taken as 122 days[1],D_r represents wood decomposition rate (mass loss over 122 days) This equation indicates the extent to which the wood has been corroded after time t.

4 Cellular Automata Simulation of Multifungal Model

4.1 Model Preparation

4.1.1 Influence of Temperature and Moisture

In order to describe the fungal growth and decomposition capacity under different environmental factors, such as temperature and moisture,We set a parameter to indicate active factor η. When the fungi is at optimum temperature and optimum moisture, the η is 1. When considering the relationship between the viability of the organism and its ecological niche, we assume that the effect of temperature and moisture on the fungi can be considered as the following relation.

$$\eta = \exp(-\frac{(T-T_0)^2}{T_1^2} - \frac{(M-M_0)^2}{M_1^2}) \tag{6}$$

Where T_0, M_0 are the optimum temperature and moisture of the fungi, and T_1, M_1 are the ecological niche width of the fungi. the larger T_1, M_1 means the fungi is less affected by environmental changes.[5]

4.1.2 Assumpions of Cell Automata

Considering that a fungal colony can be considered as an independent unit. We use cellular automata to simulate the decomposition of wood under multiple fungal interactions. We set each cell to represent a colony of area S_I for simplicity.Initially, the proportion of each fungi is fixed and occupies 0.2 of the total. We first consider the interactions between two fungi. The results are then generalized to multiple fungal interactions after the interactions between the two fungi are understood. In our first model, constant temperature and moisture are set. After verifying the correctness of the model, we then consider adding periodic perturbations to study the effect of climate change on different fungal assemblages. In the specific simulations again, fungal transmission through spores in the air is not considered, this is because spore transmission in the air is more stochastic and spreads widely, which does not affect our smaller scale models more. Based on the computational volume and model accuracy, we adopt a 100×100 cell model.

4.1.3 The Rules

Each cell has two properties, one concerning the parameters of organics and the other concerning the parameters of fungi. There are the following states of the cell: empty space, with certain organics without fungi, fungi A habitat or fungi B habitat(fungi C habitat,fungi A habitat...).

Let us consider a cell inhabited by a certain fungi whose effect on eight surrounding cells can be characterized by the proliferation probability P_{v_h}. For different species of fungi the probability (P_{v_h}), which we can assume is only related to the initial growth rate of the fungi and is proportional, has the following relationship.

$$P_{v_h} = \beta v_h \tag{7}$$

where β is a scaling factor of equal magnitude for different species of fungi, which is estimated below.

For $v_h = 5mm/day$, the fungi proliferates daily at this rate, and it is able to cover the entire cell after n days, where it satisfies.

$$n = \frac{\sqrt{S_I}}{2v_h} \tag{8}$$

which means $n = 10$;

Therefore, on the tenth day, this colony must be able to proliferate from this cell to the neighboring cells with the probability of

$$P = 1 - (1 - P_{v_h})^{8n} \tag{9}$$

We take the absolute confidence interval, i.e., we have $P \geq 0.997$.so that ,we can get $\beta = 0.014$;

And according to the definition of active factor, after taking into account the effects of temperature and moisture, the probability of proliferation to its neighboring cells becomes

$$P_{v_h} = 0.014 v_h \eta \tag{10}$$

Also, each cell inhabited by a fungi decomposes a certain maximum percentage of organics per day, and this rate of organics decomposition we characterize with the parameter P_{vc}. For different species of fungi P_{vc}, We can determine the organic matter decomposition rate v_c by next equation and equation 3.2

$$P_{v_c} t_0 = \int_0^{t_0} v_c \, dt \tag{11}$$

where t_0 is a suitable growth period, and according to the title, take $t_0 = 122day$.

The relationship between v_c and time we have given in Model 1. As in the previous discussion, when considering the effects of temperature and moisture, we can also use the active factor.

$$P_{v_c} = \frac{\int_0^{122} v_c \, dt}{122} \eta \tag{12}$$

When there are no remaining organics, the fungi inside that cell dies. And the probability (Po) of replenishing organics differs for each cell in different regions, which we used to portray the differences due to different amounts of organic matter in different regions. For calculation purposes, we also assumed that each time a cell replenishes organic matter it is always replenished to a maximum value.

The rate of energy acquisition by different fungi can also be characterized by the rate of organics decomposition (Pvc), while the faster the rate of energy acquisition is, the more competitive ability (CA) there is. The relationship between the competitive ability (CA) and the rate of organics decomposition of different fungi is as follows.

$$CA = \chi P_{vc} \tag{13}$$

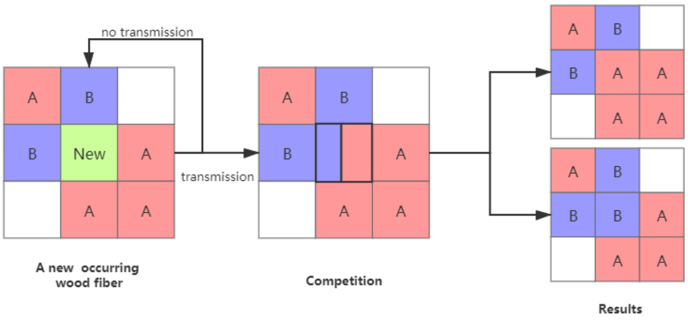


Figure 2: The proliferation process

where χ is a constant.When cells are competing, we tend to be concerned only with the relationship of relative competitive ability.

$$\frac{CA_i}{CA_j}=\frac{P_{vc_i}}{P_{vc_j}} \tag{14}$$

Based on the above conditions, it is obtained that the next evolution of a cell is determined only by the fungi in itself and in the eight surrounding cells, and after considering these fungi according to the proliferation probability, we obtain the weight factor of a certain fungi (i) in this cell , and the probability P_i that this cell evolves into the ith fungi is:

$$P_i=\frac{\varepsilon_i P_{vc_i}}{\sum_i \varepsilon_i P_{vc_i}} \tag{15}$$

ε_i is the number of the ith fungal cell proliferating in that cell. The Figure 2 represents how we can model this proliferation process in a cellular automaton.

4.2 Interaction of Two Types of Fungi

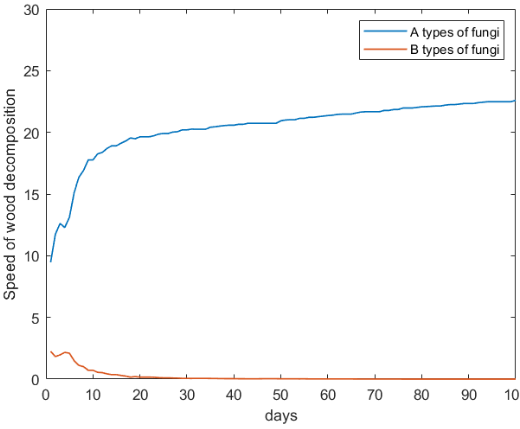


Figure 3: Competition between two fungi in the same environment

We considered the competition between two fungi A and B with the same optimum temperature, optimum moisture in the same environment. These two fungi have different adaptability to the environment. Fungus A has a faster growth rate, but it is less adaptable to the environment and it will lose its activity faster when the environment changes. While fungus B has a slower growth rate and is more adaptable to the environment. By simulating through our model, we obtained the growth curve shown in the Figure 3.

The Figure 3 illustrates that the fungus with faster growth capacity will have an absolute advantage after a certain amount of time, given a constant external environment. This is consistent with the model of culture of two competing microorganisms in a fixed environment. This could indicate the relative correctness of our model.

4.3 Settings of Environment and Fungi

Table 2: Basic Information about then mian climate (scratched from Wikipedia)[5]

	tropical rain forests	arboreal	temperate	semi-arid	arid
Temperature change $\Delta T/^oC$	± 2	± 5	± 15	± 15	± 20
moisture change ΔM	$\pm 5\%$	$\pm 10\%$	$\pm 20\%$	$\pm 10\%$	$\pm 2\%$
Rate of organics production P_0	0.004	0.003	0.002	0.001	0.0005
moisture change cycle t_M/d	365	365	365	365	365
Temperature change cycle t_c/d	365	365	365	30	15

In considering specific environments, **we considered arid, semi-arid, temperate, arboreal and tropical rain forests**, and quantified the environmental variables (Po, temperature and moisture range and temperature and moisture period) according to the different characteristics of these five environments.

When considering **the tropical rain forests and arboreal climates**, we found that the **tropical rain forests** have a smaller temperature and moisture range, a nearly constant average temperature and moisture, and the highest initial nutrient and nutrient production,**the arboreal** is similar to the tropical rain forests, but the temperature and moisture range is slightly greater than that of **tropical rain forests**. The temperate environment is the situation where the temperature and moisture fluctuate the most.

Semi-arid and arid have a smaller moisture range and a larger temperature range with the degree of aridity. And the initial nutrient and Po of the above five cases are getting smaller and smaller from tropical rain forests environment to arid environment.

Considering that the temperature and moisture in nature as a function of time is more complex, but according to the Fourier series, the temperature and moisture function can be decomposed into a series of sine and cosine functions. In the purpose of simplifying the model, we may assume that the temperature and moisture functions are sine functions plus an average temperature constant.

One very important point is that the diurnal temperature difference between **semi-arid and arid environments** is very large, so we adjusted the temperature and moisture change period downward to simulate this situation.

Therefore, based on the above relationship, we give a parameter table of the simulated environmental factors, as follows

$$T = T(0) + \Delta T \sin(\frac{2\pi t_c}{365}) \qquad M = M(0) + \Delta M \sin(\frac{2\pi t_M}{365}) \tag{16}$$

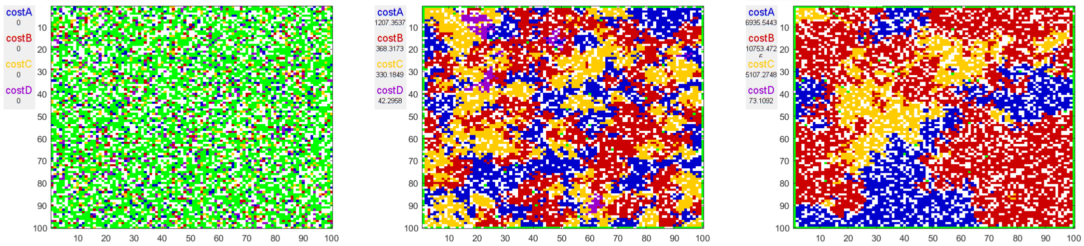
For each region, we selected four fungi A, B, C, and D. From the previous discussion, we can use mt, b, T_0, T_1, M_0, and M_1 to describe each fungi. For the fungi in the same region, according to the theory of biological evolution, we can consider that their optimum temperature T_0 and optimum moisture M_0 are equal to the average environmental temperature $T(0)$ and $M(0)$, respectively. For mt, b, T_1, and M_1, we artificially selected these parameters for each fungi so that for different fungi in the same region have the following properties due to the large interfungal variation and the lack of easy comparison.

Table 3: Characteristics of different fungi

Continent	Description
Species A fungi	Strong proliferative and competitive ability (b and mt are larger), but the least adaptive. (T_1 and $M1$ are smaller)
Species B fungi	Medium proliferative and competitive ability (both b and mt are smaller), more adaptive. (T_1 is smaller but $M_1$is larger)
Species C fungi	Proliferative and competitive abilities are the same as B, with higher adaptability. (T_1 is larger butM_1 is smaller)
Species D fungi	The ability to proliferate and compete is the weakest (b and mt are the smallest), but the most adaptive. (T_1 and M_1 are the largest)

4.4 Interaction of Four Fungi under Different Climatic Conditions

4.4.1 Tropical Fain Forest and Arboreal Climate



(a) The beginning (b) After 100 days (c) After 1000 days

Figure 4: The model of tropical rain forests

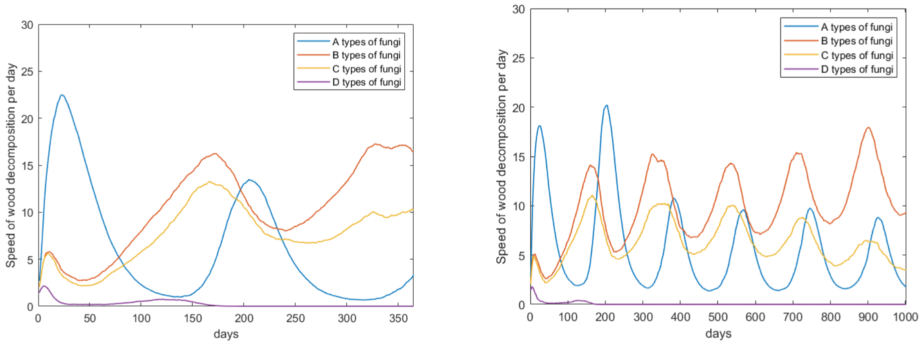
In tropical rain forests and arboreal environment, at the beginning of the simulation, due to the scene at the beginning of more nutrients, and the random scattering of fungus, fungus A, B, C, D will increase.

1. Fungus A has a strong ability to proliferate and compete, so it will be the first to seize resources and its population will increase rapidly, the rate of decomposition of organic matter also becomes faster.
2. Next, with the change of time, the temperature and moisture will change and start to deviate from the optimum point, then because of the poor adaptability of fungus A, proliferation and competition ability will start to decline.
3. BEcause fungus B,C have to better adaptive capacity than fungus A, and their proliferation and competition abilities are also moderate so the overall decomposition rates of organic matter are beyond fungus A.
4. Fungus D is too weak in competitiveness, even if it is highly adaptable, it is difficult to survive in tropical rain forests and arboreal environments due to the low variability of the environment and the strong competitiveness of competitors.

In the long term case (Figure 5b), since fungus B, C adapt to a larger interval, their total rate of decomposition of organic matter is greater than that of fungus A in the long term consideration, and the maximum rate of decomposition of fungus A is taken at the time when the temperature and moisture reach the overall average.

So in tropical rain forests and arboreal, this kind of material resources are more abundant, and less temperature and moisture fluctuations in the environment have a strong ability to proliferate and competition, so **less adaptive fungus A can survive stably. Fungus B, C have a competitive ability and adaptability so they can also survive stably**, and get slightly more energy than the fungus A. And **the fungal type D** with weak competitive value-added ability **can hardly survive** here. (Figure 5 gives the simulations of the tropical rain forests environment at 100 and 1000 days) And get slightly more energy than the fungus A.

The tropical rain forests environment also has the highest total organic matter consumption rate at 1000 days among our five scenarios, which represents the fastest carbon cycling rate in the tropical rain forests environment. **The rate of carbon cycling in the tropical rain forests environment is the fastest**.

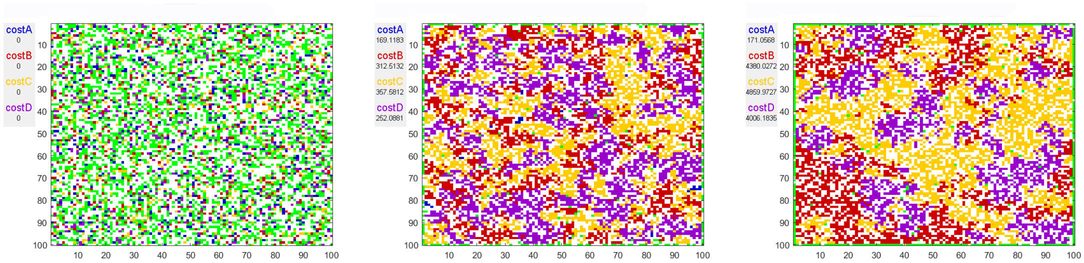


(a) Short term (b) Long term

Figure 5: Organic matter consumption in tropical rain forests

4.4.2 Temperate Climate

In the temperate environment, at the beginning of the simulation, due to the environment at the beginning of more nutrients and the fungus randomly scattered, the



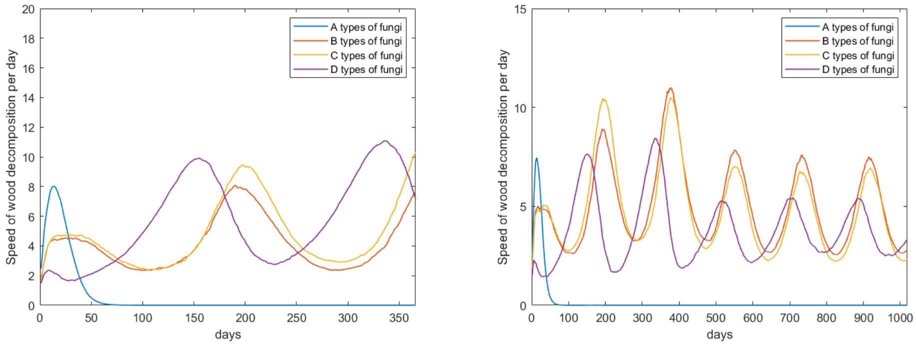
(a) The beginning (b) After 100 days (c) After 1000 days

Figure 6: The model of temperate

situation is the same as before, fungus A, B, C, D will increase (at the beginning of Figure 7a).

1. A increases the fastest, but with the increase of time, due to the temperate environment's temperature and moisture fluctuations, so the less adaptable fungus A is difficult to survive.
2. Fungus D has strong adaptability can survive in this environment (Figure 7b).
3. While fungus B, C have more moderate competitive power and adaptability, and fungus B, C at the optimum temperature to reach the maximum competitive power, so the maximum rate of decomposition of fungus B, C are in the optimum temperature to reach.

Figure 6 gives the simulated 100 days and 1000 days in temperate environment, it can be seen that in the environment of temperature and moisture fluctuation, **the more comprehensive ability of fungus similar to fungus B and C are more likely to survive, and the most adaptable fungus similar to fungus D can also survive in this environment**.

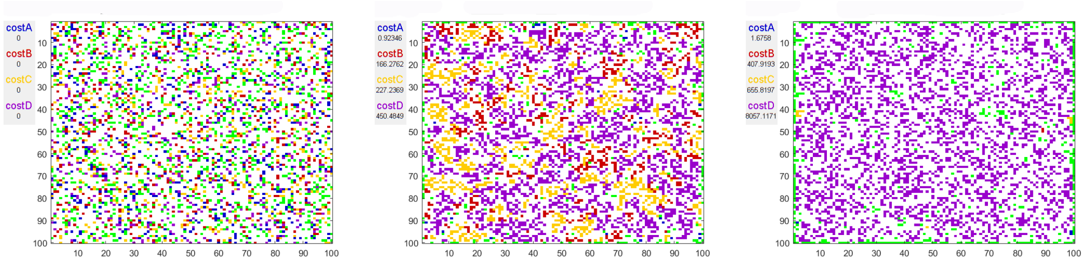


(a) Short term (b) Long term

Figure 7: Organic matter consumption in temperate

4.4.3 Semi-arid and Arid Climate

In the semi-arid and arid environments, due to the large diurnal temperature difference, so at first the more adaptable fungus D highlighted the main advantage, with the initial organic matter resources at the beginning of the decomposition rate increased



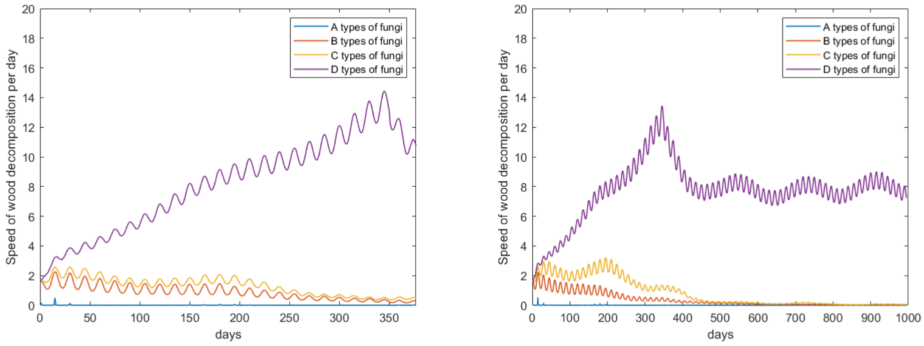
(a) The beginning (b) After 100 days (c) After 1000 days

Figure 8: The model of semi-arid

(Figure 9a), while due to adaptability the fungus A, B, C , only a small amount can be in the temperature fluctuation rate of the environment, and the lower the adaptability of the smaller the number.

1. As time grew, after the effect of initial organic matter was eliminated, the decomposition rate of fungus D varied slightly with temperature change in each day, and the overall decomposition rate showed stability.
2. Although fungus B, C were distributed in the 1000-day scenario simulated in Figure 8c, the decomposition rate of organic matter of fungus B, C was very small relative to that of fungus D because of too large temperature fluctuations.
3. Among the five environments, the arid environment is the one with the lowest rate of organic matter depletion for 100 days in our simulated cases, representing the lowest rate of carbon cycling.

Therefore, in environments similar to semi-arid and arid, with a large diurnal temperature difference and less resources, fungus D, **which are more adaptable and less able to proliferate and compete, are more likely to survive**.



(a) Short term (b) Long term

Figure 9: Organic matter consumption in semi-arid

4.5 Biodiversity Research

4.5.1 Assumptions and Research Method

In order to analyze the effect of fungal species diversity on organic matter decomposition and to predict the role of biodiversity in maintaining the stability of the local environment under changing conditions, we selected the temperate environment and its four fungal species as a reference in the previous model, and compared the effect of the initial mixed dispersal of four fungi species with the individual dispersal of fungi on the environmental carbon cycling rate. The total organic matter decomposition between t_2 ($t_2 = 3$ years) and t_1 ($t_1 = 6$ years) was used as the reference standard for the carbon cycle rate in order to eliminate the random distribution of fungi and the effect of initial organics as much as possible.

To explore the predicted role of biodiversity in maintaining the stability of the local environment when conditions change, we chose to vary the average temperature of the environment so that there is a difference between the optimum temperature of the fungi and the average temperature of the environment, and We then compared changes in carbon cycling rates for a mixture of four fungi with changes in carbon cycling rates for each of the four fungi alonewe obtain the stability of each situation in the face of varying degrees of environmental change.

4.5.2 The Results

Figure 10 shows the results we obtained by metacellular automata, and it can be found that the **carbon cycling rate obtained from the mixed dispersal of the four fungi at each ambient temperature is higher than that obtained from the dispersal of fungi A, B, C, and D alone**, which can indicate that the diversity of fungal communities of a system is beneficial to improve The overall efficiency of a system with respect to the breakdown of ground litter.

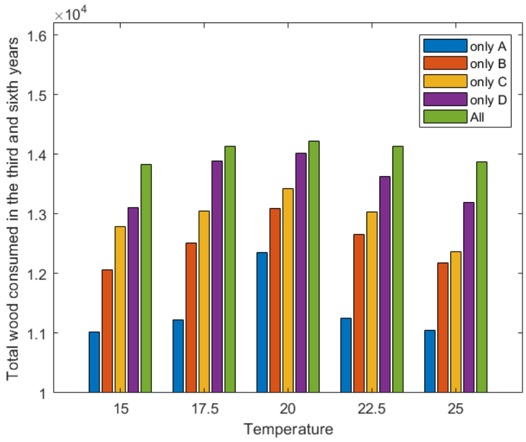


Figure 10: Comparison of decomposition capacity of single colonies and multiple fungi at different temperatures

We varied the average ambient temperature and calculated the rate of change of the decomposition rate for each temperature compared to the original temperature, and normalized the ratio.Thus we obtain the ratio of decrease of decomposition efficiency of a single strain under the influence of the overall change of temperature for each temperature (Table 4).

It can be seen that after the normalization of the decline ratio of mixed strains, **the decline ratios of four fungi, A, B, C and D, were greater than those of the mixed strains**. The decline rate of single fungal species was very high compared with the mixed fungal species when the environment changed suddenly, indicating that the mixed fungal species could maintain the carbon cycle rate more stably when the envi-

Table 4: Relative strength of adaptive capacity to environmental change

Relative values of single fungal changes relative to multiple fungi	$\frac{\text{only A}}{\text{All}}$	$\frac{\text{only B}}{\text{All}}$	$\frac{\text{only C}}{\text{All}}$	$\frac{\text{only D}}{\text{All}}$
15^oC	3.97	2.89	1.72	2.37
17.5^oC	15.76	7.47	4.83	1.50
22.5^oC	14.85	5.53	4.52	4.54
25^oC	4.30	2.83	3.18	2.38

ronmental factors changed, and the ecosystem was more stable when facing the environmental factors change.

In addition, the ratio of the decrease rate of carbon cycle rate of single fungal species to that of mixed fungal species was very large when the temperature change was small (17.5^0C vs. 22.5^0C), indicating that the single fungal species was affected more than the mixed fungal species when the environmental change was small, which indicated that the diversity of fungal species contributed more to the ecosystem temperature in the face of small environmental change.

These results suggest that **the diversity of fungal communities of a system can increase the carbon cycle rate of the ecosystem and improve the stability of the ecosystem to maintain the carbon cycle rate in the face of environmental changes**.

5 Sensitivity Analysis

In our meta-automata model, there are also some differences in the actual organics production per unit time (i.e. Po) in the same climate, and the total amount of fungi (Nf) initially dispersed randomly in our previous simulations is fixed, while the difference in Nf may also cause the difference in the final carbon cycle efficiency. Therefore, we mainly analyzed the effects of Po and Nf on the stability and sensitivity of our model.

We still chose the temperate environment, keeping other quantities constant and the fungal parameters unchanged, and measured the effect of P_o on the total amount of decomposed organic matter from the third to the sixth year within 10 points equally spaced from the interval [0.1, 0.3].

The results we obtained are shown in the figure 11 and we can see that as the amount of organics production per unit time Po increases the total amount of decomposing material per unit time increases, this is because after the ecosystem has stabilized it needs to reach energy balance, i.e. carbon balance, and the greater the amount of organics production per unit time (P_o), the greater the total amount of material decomposed by the balance. In the graph we can see that the relationship between the two is nearly linear, which is very much in line with the law of ecosystem material balance.

After that, keeping the other quantities constant and the fungal parameters unchanged, we varied the total amount of fungi initially dispersed randomly (Nf) by taking ten points equally spaced from [0.1, 0.3] and measured its effect on the total amount of decomposer mass from the third to the sixth year.

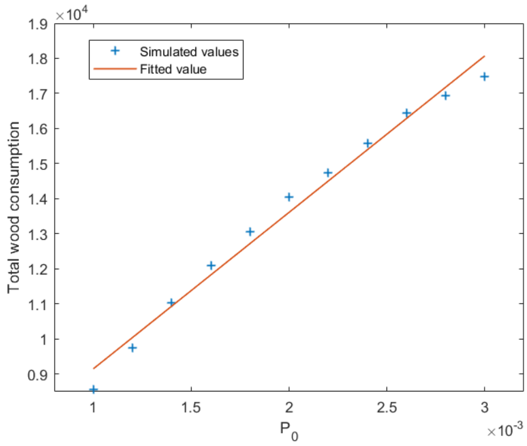


Figure 11: relationship between P_0 and total wood consumption

The figure 12 shows that the total amount of fungi initially dispersed randomly within a reasonable interval (Nf) has almost no effect on the rate of ecosystem carbon cycling at equilibrium, showing that there is almost no relationship between the state of reaching a steady state ecosystem in our model and Nf when Nf is within a reasonable interval.

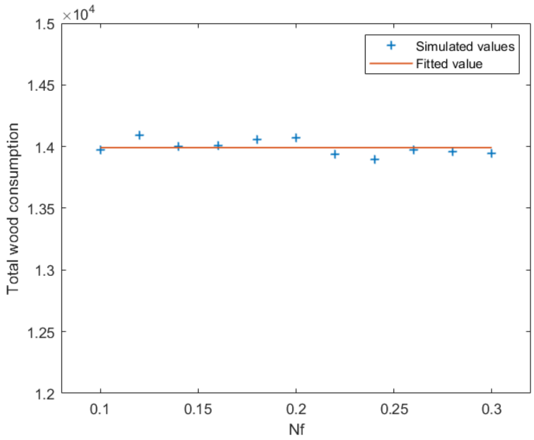


Figure 12: relationship between Nf and total wood consumption

6 Strengths and Weaknesses

6.1 Strengths

- There is a wide variety of fungi in nature, with a dozen or even dozens of species in the same region. The interactions among them are complex. We only qualitatively considered the combination of two or four species of fungi. It has some limitations.
- It has a high flexibility to simulate the environmental changes in nature and the related colony evolution by changing different parameters.
- The use of metacellular automata to model the interactions seen by multiple

fungi effectively reduces the chance of the model by choosing a larger metacellular base (10,000).

- In establishing the relationship between different parameters of a fungi, we combined the data of the topic with appropriate parameter fitting to give the exact functional relationship based on the extensive literature review.

6.2 Weaknesses

- We considered only competitive relationships when considering the effects of fungal sightings, ignoring the possible symbiotic relationships between different fungi.
- When considering fungal mortality, only fungal mortality due to food factors was considered, and fungal mortality due to harsh environments was not considered.
- There is a wide variety of fungi in nature, with a dozen or even dozens of species in the same region. The interactions among them are complex. We only qualitatively considered the combination of two or four species of fungi. It has some limitations.

Say "Hello" to Fungus

In nature, most of the energy cycle of matter is realized through the carbon cycle, and the decomposition process of organic matter in saprophytes is an integral part of the carbon cycle. Therefore, as a class of saprophytes, it is important to study the physiological activities of fungi

In the case of fungi, we focus on the nature of their daily physiological activities. At the microscopic level, we are concerned with the structure and survival conditions of fungi; at the macroscopic level, we focus on understanding the quantitative changes during the proliferation of fungi and the interactions between different fungi.

Figure 13: A tpye of fungus

We found that the decomposition ability of fungi is closely related to their growth rate and moisture tolerance, and the larger the growth rate, the stronger the decomposition ability of fungi. The faster the fungus grows, the more organic matter it needs to meet its growth rate, and the smaller the moisture tolerance, the weaker the decomposition ability of the fungus, but the more environment it can adapt to. The ability of fungal decomposition and its adaptability can help us understand the geographic distribution of fungi.

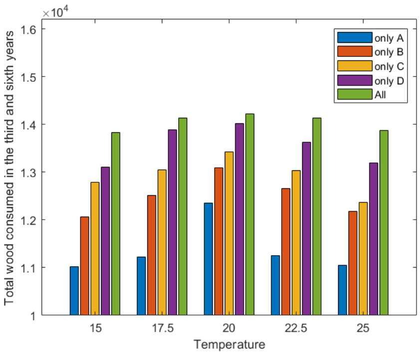


Figure 14: Comparison of decomposition capacity of single colonies and multiple fungi at different temperatures

To understand the geographic distribution of fungi with the environment. We simulated the competitive relationship of several fungi in different environments. In tropical rainforests and forests, where the temperature range is less variable and organic matter is abundant, we found that fungi with a larger Growth rate have a greater competitive advantage. In arid and semi-arid climates, where organic matter is scarce and the environment is highly variable, fungi with smaller moisture tolerance can better adapt to the environment, while fungi with larger growth rate cannot survive well due to the lack of organic matter. In contrast, the proportion of various fungi is relatively stable in temperature climates with moderate climate change and moderate organic matter.

Fungal diversity also plays an important role in the global carbon cycle. We simulated the difference in the annual decomposition of organic matter between single fungi and plural fungi in temperate zones. The results show that the annual decomposition of plural fungi is greater than that of single fungi. And it is less sensitive to environmental changes than single fungi. The plural fungi can decompose organic matter more smoothly when the environment is changed greatly.

Through this we can see the important role of fungal diversity in stabilizing the global carbon cycle.

Although we can predict the trend of fungal changes through the model, it has limitations ,because there are plenty of types of fungi in nature and there are more complex relationships among them. We hope that this article will stimulate your interest in fungal research and make their own contribution to this field in your future studies.

References

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[2] Winsor, Charles P. The Gompertz Curve as a Growth Curve. Proceedings of the National Academy of Sciences of the United States of America, vol. 18, no. 1, 1932, pp. 18.

[3] McMeekin, TA, et al. Predictive Microbiology: Theory and Application. 1993.

[4] Ayerst, G. The Effects of Moisture and Temperature on Growth and Spore Germination in Some Fungi. Journal of Stored Products Research, vol. 5, no. 2, 1969, pp. 127141.

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Appendix A: Program Codes

Here are the program codes we used in our research.

Model3.m

```
%% Clear and color settings
clear;
None=[1 1 1];Acolor=[1 0 0];Wood=[0 1 0];
Bcolor=[0 0 1];Ccolor=[1 1 0];Dcolor=[0 1 1];
%% Set GUI buttons
plotbutton=uicontrol('style','pushbutton','string','Run',
'fontsize',12, 'position',[150,400,50,20], 'callback', 'run=1;');
erasebutton=uicontrol('style','pushbutton','string',
'Stop','fontsize',12,'position',[250,400,50,20],'callback',
'freeze=1;');
quitbutton=uicontrol('style','pushbutton','string',
'Exit','fontsize',12,'position',
[350,400,50,20],'callback','stop=1;close;');
number = uicontrol('style','text','string','1',
'fontsize',12, 'position',[0,400,50,20]);
costA_Name = uicontrol('style','text','string',
'costA','foregroundcolor',Acolor,
'fontsize',12, 'position',[0,370,50,20]);
costA_Num = uicontrol('style','text','string','0',
'fontsize',8, 'position',[0,350,50,20]);
costB_Name = uicontrol('style','text','string',
'costB','foregroundcolor',Bcolor,
'fontsize',12, 'position',[0,330,50,20]);
costB_Num = uicontrol('style','text','string','0',
'fontsize',8, 'position',[0,310,50,20]);
costC_Name = uicontrol('style','text','string','costC',
'foregroundcolor',Ccolor,
'fontsize',12, 'position',[0,290,50,20]);
costC_Num = uicontrol('style','text','string','0',
'fontsize',8, 'position',[0,270,50,20]);
costD_Name = uicontrol('style','text','string','costD',
'foregroundcolor',Dcolor,
'fontsize',12, 'position',[0,250,50,20]);
costD_Num = uicontrol('style','text','string','0',
'fontsize',8, 'position',[0,230,50,20]);
set(gca,'unit','normalized');
set(plotbutton,'unit','normalized');
set(erasebutton,'unit','normalized');
set(quitbutton,'unit','normalized');
set(number,'unit','normalized');
set(costA_Name,'unit','normalized');
set(costA_Num,'unit','normalized');
set(costB_Name,'unit','normalized');
set(costB_Num,'unit','normalized');
set(costC_Name,'unit','normalized');
set(costC_Num,'unit','normalized');
set(costD_Name,'unit','normalized');
set(costD_Num,'unit','normalized');
```

```
%% Setting of initial variables
n=100;
%A,B,C,DTemperature and moisture parameters
T0a=20;T1a=10;M0a=0.6;M1a=0.2;
T0b=20;T1b=18;M0b=0.6;M1b=0.334;
T0c=20;T1c=25.05;M0c=0.6;M1c=0.24;
T0d=20;T1d=40;M0d=0.6;M1d=0.4;

Best_Pvsa=0.014*7;Best_Pvsb=0.014*6.4;
Best_Pvsc=0.014*6.4;Best_Pvsd=0.014*4.6;

Best_Pvca=Pvc(0.8,7);Best_Pvcb=Pvc(0.46,6.4);
Best_Pvcc=Pvc(0.46,6.4);Best_Pvcd=Pvc(0.27,4.6);

Po=0.003; %Amount of organic matter generated per day
%% Creating matrix logical variables and building images
%In Model(:,:,2) 0 represents open space, 1 represents
organic without fungi,
%2 represents A fungi, 3 represents B fungi,
%4 represents C fungi, 5 represents D fungi
Model = zeros(n,n,2);
temp=rand(n,n);
Model(:,:,1)=(temp)<0.5;
Model(:,:,2)=((temp<0.5&temp>0.2)+((temp)<=0.05)*2+((temp)
<=0.1&temp>0.05)*3....
        +((temp)<=0.15&temp>0.1)*4+((temp)<=0.2&temp>0.15)*5);
Color=zeros(n,n,3);
Color(:,:,1)=((Model(:,:,2)==0)*None(1)+(Model(:,:,2)==1)...
*Wood(1)+(Model(:,:,2)==2)*Acolor(1)...
    +(Model(:,:,2)==3)*Bcolor(1)+(Model(:,:,2)==4)...
    *Ccolor(1)+(Model(:,:,2)==5)*Dcolor(1));
Color(:,:,2)=((Model(:,:,2)==0)*None(2)+(Model(:,:,2)==1)...
*Wood(2)+(Model(:,:,2)==2)*Acolor(2)...
    +(Model(:,:,2)==3)*Bcolor(2)+(Model(:,:,2)==4)...
    *Ccolor(2)+(Model(:,:,2)==5)*Dcolor(2));
Color(:,:,3)=((Model(:,:,2)==0)*None(3)+(Model(:,:,2)==1)...
*Wood(3)+(Model(:,:,2)==2)*Acolor(3)...
    +(Model(:,:,2)==3)*Bcolor(3)+(Model(:,:,2)==4)...
    *Ccolor(3)+(Model(:,:,2)==5)*Dcolor(3));
% Create image handle
subplot(2,2,1);
imh = image(cat(3,Color));
subplot(2,2,2);subplot(2,2,3);subplot(2,2,4);
% Cells update row number setting
x = 2:n-1;y = 2:n-1;
sumA=zeros(n,n);sumB=zeros(n,n);sumC=zeros(n,n);sumD=zeros(n,n);
CostA=0;CostB=0;CostC=0;CostD=0;
CostA_list=[];CostB_list=[];CostC_list=[];CostD_list=[];
NumA_list=[];NumB_list=[];NumC_list=[];NumD_list=[];
%% Main Event Loop
stop= 0; run = 0;freeze = 0;
while stop==0
    if get(number,’string’)==1800
```

```
        run=0;
    end
    if run==1
        T=20+15*sin(2*pi/365*str2double(get(number,'string')));
        M=0.6+0.2*sin(2*pi/365*str2double(get(number,'string')));

        etaA=exp(-(T-T0a)^2/T1a^2-(M-M0a)^2/M1a^2);
        etaB=exp(-(T-T0b)^2/T1b^2-(M-M0b)^2/M1b^2);
        etaC=exp(-(T-T0c)^2/T1c^2-(M-M0c)^2/M1c^2);
        etaD=exp(-(T-T0d)^2/T1d^2-(M-M0d)^2/M1d^2);
        Pvsa=Best_Pvsa*etaA;Pvsb=Best_Pvsb*etaB;
        Pvsc=Best_Pvsc*etaC;Pvsd=Best_Pvsd*etaD;
        Pvca=Best_Pvca*etaA;Pvcb=Best_Pvcb*etaB;
        Pvcc=Best_Pvcc*etaC;Pvcd=Best_Pvcd*etaD;

        Model(:,:,1)=Model(:,:,1)-((Model(:,:,2)==2)*Pvca+...
        (Model(:,:,2)==3)*Pvcb...
            +(Model(:,:,2)==4)*Pvcc+(Model(:,:,2)==5)*Pvcd);
        CostA=CostA+sum(sum((Model(:,:,2)==2)*Pvca));
        CostB=CostB+sum(sum((Model(:,:,2)==3)*Pvcb));
        CostC=CostC+sum(sum((Model(:,:,2)==4)*Pvcc));
        CostD=CostD+sum(sum((Model(:,:,2)==5)*Pvcd));
        set(costA_Num,"string",num2str(CostA));
        set(costB_Num,"string",num2str(CostB));
        set(costC_Num,"string",num2str(CostC));
        set(costD_Num,"string",num2str(CostD));
        CostA_list=[CostA_list,sum(sum((Model(:,:,2)==2)*Pvca))];
        CostB_list=[CostB_list,sum(sum((Model(:,:,2)==3)*Pvcb))];
        CostC_list=[CostC_list,sum(sum((Model(:,:,2)==4)*Pvcc))];
        CostD_list=[CostD_list,sum(sum((Model(:,:,2)==5)*Pvcd))];
        NumA_list=[NumA_list,sum(sum((Model(:,:,2)==2)))/(n^2)];
        NumB_list=[NumB_list,sum(sum((Model(:,:,2)==3)))/(n^2)];
        NumC_list=[NumC_list,sum(sum((Model(:,:,2)==4)))/(n^2)];
        NumD_list=[NumD_list,sum(sum((Model(:,:,2)==5)))/(n^2)];
        subplot(2,2,2);
        plot(CostA_list,'color',Acolor);
        hold on
        plot(CostB_list,'color',Bcolor);
        plot(CostC_list,'color',Ccolor);
        plot(CostD_list,'color',Dcolor);
        hold off
        subplot(2,2,3);
        plot(CostA_list+CostB_list+CostC_list+CostD_list,'k');
        subplot(2,2,4);
        plot(NumA_list,'color',Acolor);
        hold on
        plot(NumB_list,'color',Bcolor);
        plot(NumC_list,'color',Ccolor);
        plot(NumD_list,'color',Dcolor);
        hold off

        Model(Model(:,:,1)<=0)=0;
        temp=Model(:,:,1)>0;
```

```
        Model(:,:,2)=Model(:,:,2).*temp;
        resources=Model(:,:,2);

        %
        type=2;
        p=Pvsa;
        sumA(x,y) = (resources(x,y)==type)+
        (resources(x,y-1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x,y+1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x-1, y)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x+1,y)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x-1,y-1)==type)
            .*(rand(n-2,n-2)<p) + ...
            (resources(x-1,y+1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x+1,y-1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x+1,y+1)==type).*(rand(n-2,n-2)<p);
        type=3;
        p=Pvsb;
        sumB(x,y) = (resources(x,y)==type)+...
        (resources(x,y-1)==type)*(rand(n-2,n-2)<p)+ ...
            (resources(x,y+1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x-1, y)==type)
            .*(rand(n-2,n-2)<p) + ...
            (resources(x+1,y)==type).*(rand(n-2,n-2)<p) +...
             (resources(x-1,y-1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x-1,y+1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x+1,y-1)==type).*(rand(n-2,n-2)<p) + ...
            (resources(x+1,y+1)==type).*(rand(n-2,n-2)<p);
        type=4;
        p=Pvsc;
        sumC(x,y) = (resources(x,y)==type)+...
        (resources(x,y-1)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x,y+1)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x-1, y)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x+1,y)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x-1,y-1)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x-1,y+1)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x+1,y-1)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x+1,y+1)==type).*(rand(n-2,n-2)<p);
        type=5;
        p=Pvsd;
        sumD(x,y) = (resources(x,y)==type)+...
        (resources(x,y-1)==type).*(rand(n-2,n-2)<p)+ ...
        (resources(x,y+1)==type).*(rand(n-2,n-2)<p) +...
        (resources(x-1, y)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x+1,y)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x-1,y-1)==type)....*(rand(n-2,n-2)<p) + ...
        (resources(x-1,y+1)==type).*(rand(n-2,n-2)<p) + ...
        (resources(x+1,y-1)==type)....*(rand(n-2,n-2)<p) + ...
        (resources(x+1,y+1)==type).*(rand(n-2,n-2)<p);
        % Update according to the rules
        sumA=sumA*Pvca;sumB=sumB*Pvcb;sumC=sumC*Pvcc;sumD=sumD*Pvcd;
        ratio1=(sumA)./(sumA+sumB+sumC+sumD);
```

```
        ratio2=(sumA+sumB)./(sumA+sumB+sumC+sumD);
        ratio3=(sumA+sumB+sumC)./(sumA+sumB+sumC+sumD);
        neworganics=(rand(n,n)<Po);
        Model(neworganics==1)=1;
        resources=neworganics.*(resources==0)+resources;
        rand1=rand(n,n);
        resources=(resources~=0).*(isnan(ratio1)+(rand1<=ratio1)*2+
        (ratio1<rand1&rand1<=ratio2)*3+...
        (ratio2<rand1&rand1<=ratio3)*4+(ratio3<rand1&rand1<=1)*5);
        Model(:,:,2)=resources;
        Color(:,:,1)=((Model(:,:,2)==0)*None(1)+(Model(:,:,2)==1)...
        *Wood(1)+(Model(:,:,2)==2)*Acolor(1)...
            +(Model(:,:,2)==3)*Bcolor(1)+(Model(:,:,2)==4)*Ccolor(1)+
            (Model(:,:,2)==5)*Dcolor(1));
        Color(:,:,2)=((Model(:,:,2)==0)*None(2)+(Model(:,:,2)==1)*
        Wood(2)+(Model(:,:,2)==2)*Acolor(2)...
            +(Model(:,:,2)==3)*Bcolor(2)+(Model(:,:,2)==4)*Ccolor(2)+
            ...(Model(:,:,2)==5)*Dcolor(2));
        Color(:,:,3)=((Model(:,:,2)==0)*None(3)+(Model(:,:,2)==1)*
        Wood(3)+(Model(:,:,2)==2)*Acolor(3)...
            +(Model(:,:,2)==3)*Bcolor(3)+(Model(:,:,2)==4)*Ccolor(3)
            +(Model(:,:,2)==5)*Dcolor(3));
        subplot(2,2,1);
        set(imh, 'cdata', cat(3,Color))
        stepnumber = 1 + str2double(get(number,'string'));
        set(number,'string',num2str(stepnumber))
        if stepnumber==1095
            tempCost=CostA+CostB+CostC+CostD;
        end
        if stepnumber==2200
            pause(3);Costfinal=CostA+CostB+CostC+CostD-tempCost;
        end
    end
    if freeze==1
        run = 0;freeze = 0;
    end
    drawnow
end
```

Pvc.m

```
    function A = Pvc(mt,hy)
%PVS
%
b=0.04*hy;
syms t1;
y=(10^-5*6)*exp(1.85+0.85*mt)*(0.1*0.1)^0.75*exp(0.75)...
*exp(log(100*100)*(1-exp(-b*t1)));
A=eval(int(y,t1,0,122))*0.01/122;

end
```