
Fungi and ecosystems

The biosphere carbon cycle is an important process of the earth life movement and an active part of carbon exchange in the geochemical cycle. The decomposition of plant materials and wood fibers by fungal communities is the key process of the biosphere carbon cycle.

We took the growth rate of hypha and water resistance as the factors affecting the decomposition rate of organic matter, and established the differential equation model of fungus-wood decomposition rate. After data collection, SPSS software was used to perform linear fitting of the logarithm of decomposition rate and growth rate, the logarithm of moisture tolerance, the logarithm of growth rate and the product of moisture tolerance, $R=0.848$, and $P<0.01$, the results are significant.

Considering that the growth rate of mycelia will change with the interaction between fungi, the correlation coefficient matrix was introduced, and the correlation coefficient was the ratio of the competitiveness ranking between the two fungi. We simulated the three possible interactions of competition, unilateral competition and cooperation, and the results showed that the effect was not significant in the short term. If competition occurred, the final mycelial length of the fungi with relatively strong competition only decreased from 28mm to 26mm, while the fungi with relatively weak competition decreased from 38mm to 0mm, and finally died.

We evaluated the influence of the environment on the growth and decomposition of organic matter by fungi. We selected Nebraska in the United States as the representative, and found a set of temperature and humidity fluctuation data for 100 days. After 100 days, the relative decomposition rate of fungi to organic matter was calculated to be 6.3%, compared with 8.2% under constant conditions. In addition, we also predicted the effect of atmospheric change after 10 years (0.12°C increase in average temperature and 3% increase in relative humidity), and the results showed that the impact of slowly progressing atmospheric change was small.

In order to predict the relative strengths and weaknesses of species and species combinations in different environments, environmental fitness was first defined. Then, we selected 4 fungi and 6 combinations composed of them in two to calculate their environmental fitness respectively. Among the 4 fungi isolated from culture, *Amillaria gallicad* had the highest environmental fitness (74.347), while among the 6 fungal combinations, *Amillaria gallica* and *Hyphoderma setigerum* had the highest overall environmental fitness (78.868). Finally, the simulation results in arid, semi-arid, temperate, arboreal and tropical rain forest environments were carried out by our previous model, and the results were consistent with the predictions.

The importance of diversity on environmental decomposition efficiency was analyzed. According to calculation, when there were four different fungi, if one of the homologous bacteria *Amillaria sinapina* became extinct and was replaced by another homologous bacteria, the decomposition rate would change from 11% to 10.8%. If the non-homologous *Phlebia acerlha* was extinct and replaced by the other three species, the final decomposition rate changed from 11% to 3.2%. This shows the importance of biodiversity. Finally, we also used Monte Carlo simulation, and the results showed that the environmental fitness between the combinations increased significantly with the increase of fungal species.

Finally, we also analyze the sensitivity of the model. Two different fungi, *Phlebia acerina* and *Pellinus hartigii*, were simulated and the humidity was changed, and the simulation was carried out again. It turns out that the results of our model are consistent with the fact that fungi that decompose more slowly have a better ability to adapt to changes in environmental humidity.

Keywords: fungi, extension rate, moisture tolerance, decomposition rate

Contents

| | |
|--|----|
| 1 Introduction. | 2 |
| 1.1 Problem Background | 2 |
| 1.2 Restatement of the Problem | 2 |
| 2 General Assumptions. | 3 |
| 3 Notations | 3 |
| 4 Model I: Fungus-wood decomposition rate model | 3 |
| 4.1 Logistic Equation of Fungal Wood Decomposition Rate | 4 |
| 4.2 The interaction between different fungi | 6 |
| 5 Analysis and Description of the Model I | 7 |
| 5.1 Competitive parameter analysis | 7 |
| 5.2 The dynamics of the interaction | 8 |
| 5.2.1 Case 1: Competitive with each other | 8 |
| 5.2.2 Case 2: Cooperate with each other | 10 |
| 5.2.3 Case 3: One-way promotion | 12 |
| 5.3 Sensitivity to rapid fluctuations in the environment | 13 |
| 5.4 The effects of atmospheric change | 14 |
| 6 Model 2: comparative advantage prediction model | 16 |
| 6.1 Definitions of comparative advantages and disadvantages | 16 |
| 6.2 forecast relative advantages and disadvantages in different climates | 17 |
| 7 the description of biodiversity | 19 |
| 7.1 The impact of biodiversity on overall efficiency | 19 |
| 7.2 The importance and role of predicting biodiversity | 20 |
| 8 Strengths and Weaknesses. | 21 |

1 Introduction

1.1 Problem Background

The biosphere carbon cycle is an active part of carbon exchange in the geochemical cycle, in which the decomposition of plant materials and wood fibers by microbial and fungal communities is the key process of the biosphere carbon cycle. Recent studies have found that soil fungi account for 81% – 95% of the total microorganisms, which plays an important role in the plant-soil-atmosphere carbon cycle. The extension rate and the moisture tolerance are two key characteristics of fungi in the process of decomposition of wood fiber. With the larger hyphal extension rate and the better moisture tolerance, the fungus is more likely to decompose wood faster. Studies have shown that slow-growing strains of fungi tend to be able to better adapt to environmental changes such as humidity and temperature and grow stably, but the faster-growing strains are less adaptable to the same changes. Therefore, in different environments, decomposition is bound to be affected accordingly as conditions change. Consequently, it is of great significance to study the interaction of different fungi in different environments to decompose plant materials and wood fibers in the corresponding soil.



Figure 1: The fungi on the rotten wood

1.2 Restatement of the Problem

Requirement 1

- Build a mathematical model to describe the decomposition of plant material and wood fibers through fungal activity in the presence of multiple fungi.
- According to the different extension rates and moisture tolerance of fungi, the interaction between different species of fungi needs reflecting in the model.

Requirement 2

- Provide a model analysis and describe the interactions between different species of fungi. The dynamics of the interactions should be described and characterized, including short- and long-term trends.
- The model analysis needs to include sensitivity to rapid fluctuations in the environment.
- Determining the overall impact of changing atmospheric trends to assess the impact of changes in local weather patterns.

Requirement 3

- To predict the relative strengths and weaknesses of each species and possible combinations of species.
- The same prediction needs making for different environments, including arid, semi-arid, temperate, arboreal and tropical rain forests

Requirement 4

- Describe how the diversity of a fungal community system affects the overall efficiency of the system in decomposing plant materials and wood fibers
- Predict the importance and role of bio-diversity in the presence of different degrees of variability in the local environment.

2 General Assumptions

- The results are focused on the middle stage of decomposition and it is consistent for other stages.
- The effect of resource consumption on the growth of one population is the same as that on the growth of the other.
- under the weather condition in this paper, when fungi stop growing due to environmental factors, they will not die, but maintain a static state of growth. When temperature and humidity return to an appropriate value, fungi can resume their growth.

3 Notations

Table 1:Main Notations

| Variable | Description |
|----------------|---|
| $r_i(t)$ | The extension rate of the fungi _{<i>i</i>} |
| h_i | The moisture tolerance of fungi _{<i>i</i>} |
| R_i | The compete rank of the fungi _{<i>i</i>} |
| W_i | The moisture niche width of the fungi _{<i>i</i>} |
| $\lambda_i(t)$ | The resulting wood decomposition rate of the fungus <i>i</i> at time <i>t</i> |
| g_i | The natural growth rate of the fungus <i>i</i> |
| $x_i(t)$ | The hyphal length of the fungus <i>i</i> at time <i>t</i> |
| σ | The competition coefficient |

4 Model I: Fungus-wood decomposition rate model

For the task 1, which requires the establishment of a mathematical model for the decomposition of plant materials or wood fibers by fungi in the presence of different species of fungi. The degree to which ground litter and woody fibers is decomposed in this paper is measured by the relative remaining percentage of plant materials

or wood fibers. Time-dependent wood quality was affected by fungal decomposition rate. The decomposition rate was mainly affected by hyphae elongation and moisture tolerance. The growth rate and moisture tolerance may change over time, and therefore the decomposition rate may also change over time, thus establishing a differential equation model for the fungal-wood decomposition rate. Because of the presence of different species of fungi in the environment, groups of fungi can interact with each other, either competing with each other, or depending on each other, possibly without any problems. The interaction between fungi mainly affects the growth rate of fungi. Meanwhile, the influence of environmental factors on the natural growth rate of fungi should be considered to reflect the interaction between fungi in the model. The idea of model establishment is shown in the following figure:

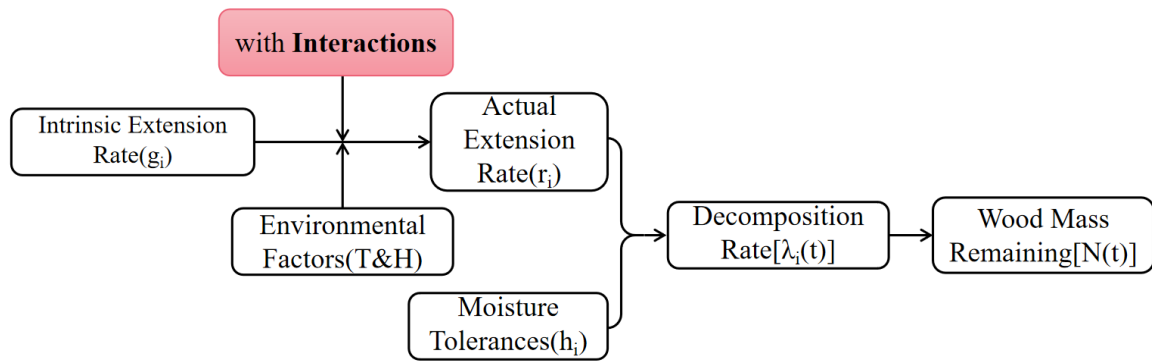


Figure 2: Flowchart of Model I Establishment

4.1 Logistic Equation of Fungal Wood Decomposition Rate

It is known that fungal decomposition of wood is mainly affected by two characteristics. One of these important characteristics is the rate of growth of the fungus $r_i(t)$, and the other is the moisture tolerance of the fungus h_i .

- Effect of growth rate on decomposition rate

According to reference A, when the logarithm of growth rate and decomposition rate is taken, there is a certain linear relationship. Therefore, 30 species of fungi were randomly selected, and logarithms of their growth rate and decomposition rate were taken respectively to establish a linear regression model.

$$\begin{cases} \lg \lambda_i(t) = A \lg r_i(t) + a \\ \lambda_i(t) = r_i(t)^A \cdot 10^a \end{cases} \quad (1)$$

Then, we tested the model with the analysis of variance, and selected $\alpha = 0.05$ as the test level to test the significance of each coefficient.

The results are as follows:

$R=0.736$, the fitting effect is general; The result of ANOVA $F=33.074$, $P<0.01$, significant.

- Effect of moisture tolerance on decomposition rate

It can be seen from the literature that there is a certain linear relationship between the decomposition rate and the moisture tolerance after logarithmic decomposition rate. The previous data of 30 species of fungi were selected to take logarithmic decomposition rate and then linear regression analysis was conducted between the decomposition rate and the moisture tolerance.

$$\begin{cases} \lg \lambda_i(t) = Bh_i + b \\ \lambda_i(t) = 10^{Bh_i+b} \end{cases} \quad (2)$$

Then the test was performed in the same way.

The results are as follows:

$B=0.348$, $b=0.499$, $R=0.578$, the fitting effect is poor; The result of ANOVA $F=14.053$, $P=0.01$, significant.

Since neither growth rate nor moisture tolerance fitting decomposition rate was satisfactory, the combination of growth rate and moisture tolerance fitting decomposition rate was considered. Similarly, the previous data of 30 species of fungi were selected to take logarithms of their growth rate and decomposition rate respectively. Since there may be some relationship between growth rate and moisture tolerance, an item $\log(r_i) \cdot h_i$ was added, and the three items were fitted together. Multiple linear regression model is established as follows:

$$\log(\lambda_i) = k_1 \log(r_i) + k_2 h_i + k_3 \log(r_i) \cdot h_i + b \quad (3)$$

The results are as follows

$$\lambda_i = 10^{0.092 \log(r_i)} \cdot 10^{0.212 h_i} \cdot 10^{0.668 \log(r_i) \cdot h_i} \cdot 10^{0.482} \quad (4)$$

From this, the relationship between decomposition rate and growth rate and moisture tolerance can be drawn.

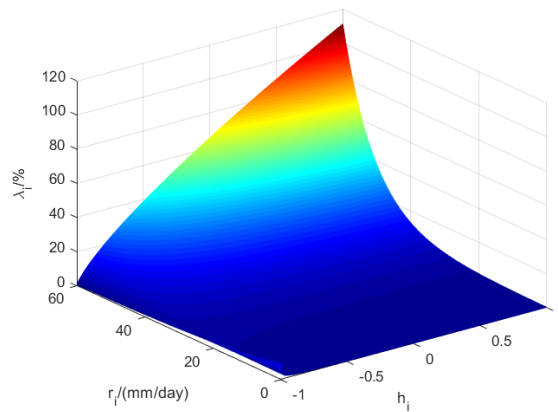


Figure 2: Fit the 3D diagram

Under the action of fungal decomposition, the weight of wood N decreased gradually with time. Therefore, after the wood mass at time t passes through time Δt , the mass decomposed by fungi can be expressed as

$$N(t + \Delta t) - N(t) = -\lambda N(t) \cdot \Delta t \quad (5)$$

4.2 The interaction between different fungi

The growth rate of fungi can be expressed as the following formula

$$r_1(t) = g_1 x_1(t) \left[1 - \frac{x_1(t)}{N_1} - \sigma_1 \frac{x_2(t)}{N_2} \right] \quad (6)$$

Similarly, another fungus can be expressed in the same way as above. It is worth noting that this paper assumes that the two fungi have equal blocking effects on each other in the process of competition, which can be expressed as the following formula

$$1 : \sigma_1 = \sigma_2 : 1 \quad (7)$$

A matrix H is introduced to represent the competition coefficient between fungi

$$H = \begin{pmatrix} 1 & \sigma_{12} & \cdots & \sigma_{1j} \\ \sigma_{21} & \sigma_{22} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{i1} & \sigma_{i2} & \cdots & 1 \end{pmatrix} \quad (8)$$

In this paper, the competition coefficient among fungi is based on the competitive ranking coefficient of fungi R , which can be expressed as

$$\begin{cases} \sigma_{ij} = \frac{R_j}{R_i} \\ \sigma_{ji} = \frac{1}{\sigma_{ij}} \end{cases} \quad (9)$$

When multiple fungi exist in the environment, the growth rate $r_i(t)$ of a certain fungus at the time of t can be expressed as the differential equation of the mycelial length of the fungus at the time of t , as shown below:

$$r_i(t) = \frac{dx_i(t)}{dt} = g_i x_i(t) \left[1 - \sum_{j=1}^n H_{ij} \frac{x_j(t)}{N_j} \right] \quad (10)$$

The environment factor E is expressed as

$$E(T, M) = \frac{1}{\sigma_1 \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{T - \mu_1}{\sigma_1} \right)^2} \cdot \frac{1}{\sigma_2 \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{M - \mu_2}{\sigma_2} \right)^2} \quad (11)$$

Therefore, to obtain E , we need to obtain 4 parameters, namely the standard deviations and mean values of the two normal distribution probability density functions. For a certain fungus, the optimum temperature or humidity can be known through experiment or query data, so as to estimate the mean value of its probability density function μ_1 and μ_2 . At the same time, according to the definition of niche width, the abscissa value when the normal distribution probability density function is one half of its maximum value is the niche width value of temperature or humidity, and then the abscissa value is about $\mu \pm 1.17 \sigma$, so it can be estimated that $\sigma_1 = T_I^w / 2.34$. Therefore, the four parameter estimation methods are as follows:

$$\begin{cases} \mu_1 = T_i^* \\ \mu_2 = M_i^* \\ \sigma_1 = T_i^w/2.34 \\ \sigma_2 = M_i^w/2.34 \end{cases} \quad (12)$$

In conclusion, when multiple fungi are present in the environment, the decomposition rate of wood changes due to the interaction between fungi and the influence of the environment on fungi. Therefore, the fungal-wood decomposition rate model can be completely expressed as the following formula

$$\begin{cases} r_i(t) = \frac{dx_i(t)}{dt} = g_i x_i(t) [1 - \sum_{j=1}^n H_{ij} \frac{x_j(t)}{N_j}] \mathbf{E}(T, M) \\ \lambda_i(t) = r_i^A(t) \cdot 10^{Bh_i+b+a} \\ \frac{dN}{dt} = - \sum_{i=1}^n \lambda_i(t) N(t) \end{cases} \quad (13)$$

5 Analysis and Description of the Model I

5.1 Competitive parameter analysis

The interaction between different populations of fungi was mainly affected by the competition coefficient of fungi σ_{ij} , which affected the growth rate and changed the decomposition rate, and finally led to the change of wood decomposition. Therefore, it is very important to discuss the competition coefficient between fungi. According to formula (10), σ_{ij} is equal to the ratio of competitive ranking of fungus j to competitive ranking of fungus I . When two fungi are present in the environment, their mycelial elongation can be expressed as

$$\begin{cases} r_1(t) = g_1 x_1(t) [1 - \frac{x_1(t)}{N_1} - \sigma_1 \frac{x_2(t)}{N_2}] \\ r_2(t) = g_2 x_2(t) [1 - \frac{x_2(t)}{N_2} - \sigma_2 \frac{x_1(t)}{N_1}] \\ \sigma_1 = \frac{R_2}{R_1} \end{cases} \quad (14)$$

According to the above formula, it can be concluded that when the two fungi are in competition with each other, the competition coefficient is $\sigma_{ij} > 0$, the growth rate decreased. At the same time, the more competitive the fungi were, the higher the competitive rank R_I was, the smaller the competitive coefficient σ_I was, and the less the inhibition degree of mycelium elongation $R_I(t)$ was. On the contrary, the less competitive fungi also have competitive effects, but they are strongly inhibited by the more competitive fungi, and their elongation reaches negative value more quickly, so that the fungi eventually die.

When the two fungi are cooperative, the meaning of competition coefficient σ_{ij} changes. There is no competition between the two fungi, but they provide each other with the required resources. So, $\sigma_{ij} < 0$, the growth rate increased.

When one fungus promotes the growth of another in one direction, the promoted fungi, competing for resources, inhibit the growth of the promoted fungi in the long

$\text{run}.\sigma_{ij}\sigma_{ji} < 0$, the mycelial elongation of the promoted fungi increased, while the promoted fungi were inhibited.

5.2 The dynamics of the interaction

5.2.1 Case 1: Competitive with each other

Suppose there are two types of fungi on a fixed ground. These two types of fungi compete with each other for resources, so that their growth rate and decomposition rate change, and finally affect the decomposition of wood. According to the data in Table 1, the competitive ranking of the two types of fungi can be obtained. When two fungi compete with each other, the competitive gap between the two fungi can be obtained by means of competitive ranking, and the competitive coefficient can be calculated. As a result, the growth rate, decomposition rate and other characteristics of the two fungi were inhibited compared with those of the two fungi alone. However, when a fungus becomes too competitive with another fungus, its own growth is inhibited, but the growth of the other fungus is severely inhibited, resulting in its death.

To simulate the interaction between different fungal populations, two competing fungi, *Armillaria sinapina* PR9 and *Armillaria gallica* OC1.

According to the simulation process, the elongation length, decomposition rate and wood decomposition of the two fungi under the condition of independent growth and competition are shown in the figure below

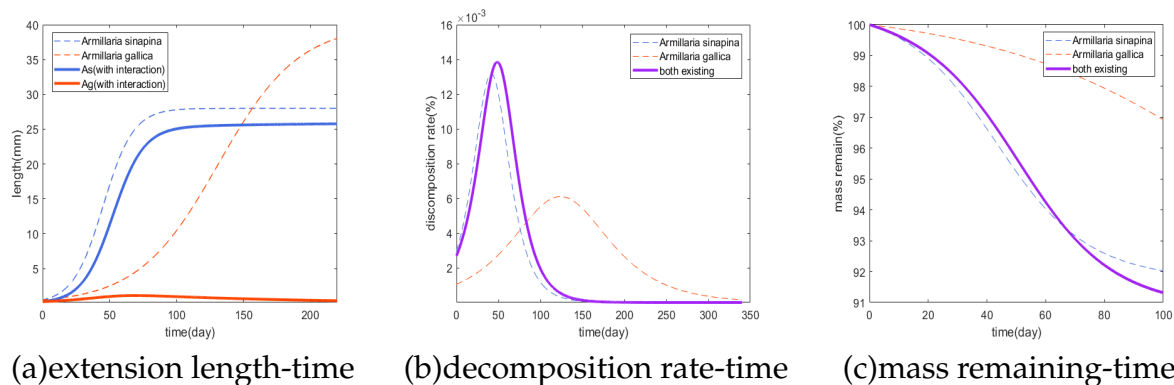


Figure 3:Dynamic characteristics of fungi in a competitive relationship

Where, the solid line shows the results when the two fungi are present and competing with each other, and the dotted line shows the results when the fungi are in the environment alone.

- Growth

According to Fig.3(a), the elongation length of both fungi in the competitive state decreased compared with that in the separate state.

As can be seen from the above table x , the blue *As* fungus has a higher competitive ranking than the red *Ag* fungus. Therefore, blue fungi have stronger competition and lower competition coefficient, and are less inhibited by red fungi, and the extension length of mycelium is slightly reduced. Under the condition of the presence of blue fungus alone, the extension length of 82 day reached the peak value of 28.8mm; In the competitive state, the peak length of blue fungi decreased, the time to reach the peak

increased, and the time to reach the peak remained stable after reaching the peak, but the time to reach the peak was not shown in the figure.

The competition of red fungi is lower than that of blue fungi, so the competitiveness is less than that of blue fungi, and the extension length of mycelium is significantly reduced by its inhibition degree, and even tends to die. Under the condition of red fungus alone, the extension length of 233 days reached the peak value of 38.17 mm. In the competitive state, 61 days reached a peak of 1.7 mm and then declined and gradually died.

⇒ Short term dynamic characteristics

In the case of mutual competition, although the fungi inhibit each other, but in the short term, the growth of the fungus is less than the speed and range of independent existence. It is worth noting that fungi with high competitive ranking will not fluctuate in the short term and grow steadily. However, the fungi with low competitive rank were inhibited by the fungi with high competitive rank in the short term, and reached the peak rapidly, and the range was much lower than that of the fungi alone.

⇒ Long term dynamic characteristics

In the process of long-term mutual competition, the highly competitive fungi gradually reached the peak and tended to be stable. The mycelial elongation length of the less competitive fungi decreased gradually and the fungi tended to die. This was in line with previous expectations.

- Decomposition rate

According to Fig. 3(b), although the two fungi compete with each other, the peak value of the total rate of wood decomposition is greater than that of the fungi alone because of the presence of the two fungi. When alone, blue fungus 48 days reaches maximum decomposition rate of $13.1 \times 10^{-3}\%$; Red Fungi 129 days reaches maximum decomposition rate $6.1 \times 10^{-3}\%$. While the total decomposition rate of 51 days reached a peak of $13.9 \times 10^{-3}\%$.

Because the competition of blue fungi was higher than that of red fungi, elongation tended to be stable after reaching the peak value. However, the elongation of red fungi decreased gradually after reaching the peak value, and the decomposition rate of wood also decreased. Therefore, the variation trend of total decomposition rate under the competitive state is similar to that of blue fungi.

⇒ Short term dynamic characteristics

According to *Model I*, the decomposition rate of fungi is related to mycelium elongation and moisture resistance. For certain fungi, the moisture resistance is a fixed value, so the decomposition rate of certain fungi changes with the change of elongation. Under the competitive condition, the rate of decomposition increased gradually in the short term as the growth rate of the two fungi continued to increase, until the peak.

However, since the total length of the initial mycelia was controlled to remain unchanged in the experiment, the initial decomposition rate would present a relative compromise situation compared with the decomposition process of a single mycelia, so the total decomposition rate in the short term was smaller than that of the competitive fungi alone.

⇒ Long term dynamic characteristics

In the process of long-term mutual competition, the fungi with high competitive ranking kept stable after reaching the peak value and no longer grew. The less compet-

itive fungi were inhibited and tended to die. Therefore, a decrease in the growth rate leads to a gradual decrease in the decomposition rate, which eventually equals 0.

- Woody decomposition

Wood decomposition is affected by decomposition rate, so the dynamic characteristics are roughly similar to the trend of decomposition rate. Together, the two fungi decompose more wood and take less time to reach equilibrium than if they were alone. Alone, the blue fungus tended to balance after decomposing wood at 138 and stopped decomposing, leaving 91.7% of wood. Red fungus decomposes 321 after day, remaining 89.8% of wood. When there is a 100 / day split balance, the remaining wood is 90.8%.

⇒ Short term dynamic characteristics

In the short term, the wood was decomposed gradually at a rate between the two fungi alone. The rate of decomposition increases as the less competitive fungi die off.

⇒ Long term dynamic characteristics

In the process of long-term competition between fungi, with the growth rate of fungi tends to balance, decomposition rate tends to 0, wood decomposition is no longer decomposed. It is important to note that in the long term dynamic process, the wood is not completely decomposed. Fungi don't grow indefinitely, and wood is constantly replenished.

5.2.2 Case 2: Cooperate with each other

On a fixed ground, the two fungi also cooperate and promote each other, which is also a kind of interaction relationship. The growth rate and decomposition rate of the fungi are both higher when they cooperate with each other than when they exist alone. In order to simulate the interfungal cooperation, two cooperating fungi, *Amillaria sinapina* PR9 and *Laetiporus conifericola* C8b, were selected. The relevant data of these two fungi are shown in the table.

Using *MATLAB*, it is similar to the method of simulating the competition between two fungi. According to the simulation process, the elongation length, decomposition rate and wood decomposition of the two fungi under the condition of independent growth and cooperation are shown in the figure below.

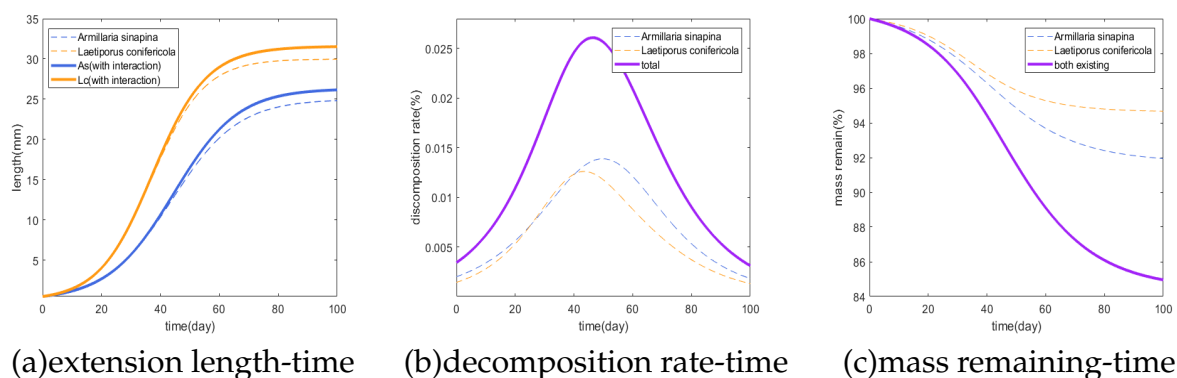


Figure 4: Dynamic characteristics of fungi in cooperative relationships

- Growth

According to Figure 4(a), the elongation length of two fungi increased when they cooperated with each other than when they existed alone.

When the yellow fungus was alone, the extension length of 65day reached the peak value of 29.2mm. In cooperation, the peak value of yellow fungi increased, the time to reach the peak decreased, and remained stable after reaching the peak value. When the blue fungus was alone, the extension length of 84day reached the peak value of 24.8mm. In the cooperative state, 78day reached a peak of 26.7mm, and then gradually leveled off.

⇒ Short term dynamic characteristics

In the process of mutual cooperation, the fungi showed a stable growth trend in the short term, and did not appear large fluctuations, and the growth rate and range were larger than that of the single existence.

⇒ Long term dynamic characteristics

In the process of long-term mutual cooperation, all fungi tend to be stable and mutualistic

- Discomposition rate

Figure 4(b) shows the total decomposition rate when the fungus is in cooperation with each other and the decomposition rate when the fungus is alone. Since the decomposition rate was affected by the growth rate, the growth rate of both fungi increased in the cooperation, so the peak value of the total decomposition rate of wood was significantly higher than that of the fungi alone. Alone, the yellow fungus 45day reached the maximum decomposition rate of 0.012%; Blue Fungi 56days reach maximum decomposition rate of 0.014%. While the total decomposition rate of 50day reached a peak of 0.026%.

Although the growth rate of yellow fungi is higher than that of blue fungi, the decomposition rate of yellow fungi is lower than that of blue fungi due to the influence of moisture tolerance.

⇒ Short term dynamic characteristics

In the cooperative relationship, in the short term, as the growth rate of the two fungi continued to increase, the decomposition rate increased gradually until the peak.

⇒ Long term dynamic characteristics

During the long term cooperation, the growth rate of various fungi remained stable after reaching the peak and no longer grew. So, the rate of decomposition goes down, and then it's equal to 0.

- Woody decomposition

When the two fungi cooperate with each other, they decompose significantly more wood than the fungi alone and take longer to reach equilibrium. Alone, the yellow fungus tended to balance after decomposing wood at 112, leaving 95.2% of wood. Blue Fungi decomposes 156days after leaving 91.8% of wood. When working together, 208days reaches breakdown balance, leaving 84.1% of wood left.

⇒ Short term dynamic characteristics

During the short term of the collaboration, the wood was decomposed rapidly, at a rate greater than that of the fungi alone, and at a degree significantly greater than that of the fungi alone.

⇒ Long term dynamic characteristics

In the long-term cooperation, the decomposition rate of fungi drops to 0, and the wood is no longer decomposed, but the wood will not be decomposed completely.

5.2.3 Case3:One-way promotion

In the ecosystem, there is one kind of interaction relationship which is unidirectional promotion relationship. It was assumed that there was a unidirectional promoting relationship between two fungi in the environment, and *Phlebia acerina* A8a and *Laetiporus conifericola* C8b were selected as simulation objects. *MATLAB* simulates the dynamic process of one-way promotion, and the results are shown in the figure below:

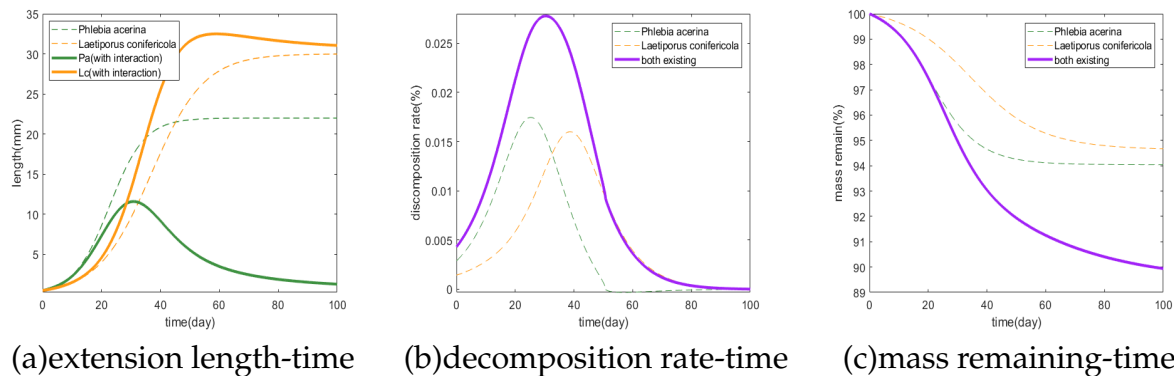


Figure 5: The dynamic characteristics of fungi under unidirectional promotion relationship

- Growth

In the unidirectional promotive relationship, the elongation length of promoted fungi was larger than that in the unidirectional promotive relationship. The extension length of the promoting fungi was reduced by the inhibition of the promoted fungi.

Figure 5(a) showed that the yellow fungus was the promoted fungus. When the yellow fungus was alone, the extension length of 76 reached the peak value of 29.4mm. In the unidirectional promotion relationship, the maximum elongation length of yellow fungus moved upward, the time to reach the peak was shortened, and then decreased slowly.

Green fungi, as promoting fungi, were inhibited by yellow fungi, and the extension length of mycelia was significantly reduced, and even tended to die. Under the condition of green fungi alone, the extension length of 46 day reached the peak value of 22.1mm; In the unidirectional promoting relationship, 31 day peaked at 12.4mm and then declined and gradually died.

⇒ Short term dynamic characteristics

In the case of unidirectional promotion, fungi showed a trend of growth in the short term, and the growth rate and range of the promoted fungi were higher than that of the promoted fungi alone, while that of the promoted fungi was just the opposite. It is worth noting that the promoted fungi grow faster and at a higher rate than the promoted fungi in the short term. It may be that the promoted fungus is able to rely on growth as it grows up to a certain point.

⇒ Long term dynamic characteristics

In a long period of unidirectional promotion, the active growth of the fungi was promoted until the peak. As the promoting fungi were inhibited and gradually died, the promoted fungi lost their supporting role and the growth rate decreased gradually.

- Decomposition rate

According to Fig. 5(b), the peak value of the total decomposition rate under unidirectional promotion was greater than that under the presence of fungi alone. When alone, the green fungus 24day reached the maximum decomposition rate of 0.0175%; Yellow fungi 42days reach maximum decomposition rate 0.158%. While the total decomposition rate of 32day reached a peak of 0.03%.

⇒ Short term dynamic characteristics

In the unidirectional promotion, the decomposition rate increased gradually until the peak due to the growth rate of the two fungi increased in the short term.

⇒ Long term dynamic characteristics

In the long-term one-way promotion process, the promoted fungi were inhibited and tended to die. After the promoted fungi reached the peak, the decomposition rate also decreased gradually due to the loss of support function. Therefore, the total decomposition rate drops rapidly after reaching the peak and finally drops to 0.

- Woody decomposition

When the two fungi were present together, they decomposed more wood than when they were alone and took longer to reach equilibrium. Alone, the yellow fungus decomposes wood at 88 to reach equilibrium and no longer decomposes, leaving 94.8% of wood. Green Fungi decomposes 66 days after leaving 94.1% of wood. In one-way promotion, 123day reaches decomposed equilibrium, leaving 89.7%.

⇒ Short term dynamic characteristics

In a short period of time, the wood was decomposed rapidly, at a rate greater than that of fungi alone, and the degree of decomposition was significantly higher than that of fungi alone.

⇒ Long term dynamic characteristics

In the long-term process of unidirectional promotion, with the gradual death of promoting fungi, the decomposition rate of promoted fungi decreased gradually, and the total decomposition rate also decreased gradually, and the wood was no longer decomposed when it was reduced to 0. Again, wood doesn't break down completely.

5.3 Sensitivity to rapid fluctuations in the environment

By analyzing the sensitivity of *Model I* to the environment and combining formula (12)(13), it can be seen that environmental factors mainly affect the mycelial elongation of fungi, thus affecting the decomposition rate, resulting in the change of wood decomposition. Environmental factors mainly include temperature and humidity, which are assumed to follow a normal distribution over time. In order to check the sensitivity of the model to the rapid fluctuation of the environment, this paper collected the temperature and humidity data of 68, 100 days in Nebraska, USA, and took the fungus of *Armillaria Sinapina*, as the object for simulation analysis. Since the rapid environmental fluctuations are mainly concerned with the short-term dynamic processes of fungi, the interaction between fungi does not need to be considered.

First of all, select one group of data and use *MATLAB* to put the data into the formula (12) and (13), so as to figure out the variation curve of the extension length, decomposition rate and wood decomposition of *AS* fungus in this region within 100 days. The results are shown in the figure below

The decomposition rate of fungi is affected by growth rate and moisture tolerance. Since moisture tolerance is an inherent property of fungi, environmental factors mainly

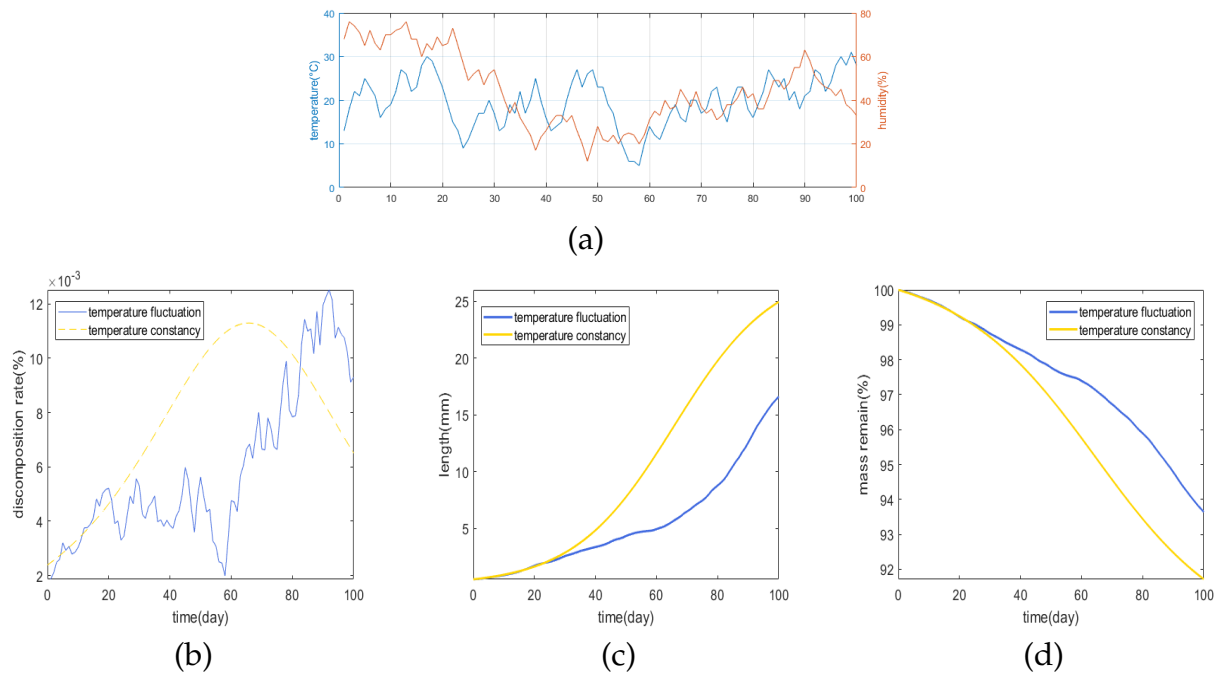


Figure 6: Effects of rapid environmental fluctuations on characteristics of fungi

change the growth rate of fungi and thus affect the decomposition rate. It can be seen from Figure (6) that the rapid and large fluctuation of environmental factors will lead to significant fluctuations in the growth rate and decomposition rate of fungi, which will weaken the effect of decomposed wood and increase the residual weight of wood.

As shown in Figure (6), when temperature and humidity decreased, the growth rate of fungi decreased significantly, so the elongation length of fungi tended to balance and no longer elongated, leading to a decrease in decomposition rate. Among them, between 50 and 60 days, the range of environmental change is the largest, and the temperature drops to the lowest, which leads to the inhibition of fungal growth, unchanged length, the decomposition rate drops to the lowest, and the remaining wood mass tends to balance. After that, the temperature and humidity gradually rose, the growth rate of fungi increased rapidly, the decomposition rate also fluctuated, and the remaining wood mass decreased rapidly and finally reached equilibrium.

In conclusion, when the environmental factors fluctuate rapidly, the model can better change the corresponding results, reflecting a good sensitivity.

5.4 The effects of atmospheric change

Atmospheric changes mainly affect temperature and precipitation, and with the increase of carbon emissions from human activities, the atmosphere also changes accordingly. According to relevant data, the global average temperature has been rising at a rate of about 0.16°C per decade since 1979. Zonal mean total precipitation increased at all latitudes except the northern subtropics (15° - 30°N) and south Asia to mid-latitudes (30° - 40°S).

So the overall effect of atmospheric trends is a slight increase in temperature over time and a slight increase in humidity.

Using Nebraska as the simulation site, the average temperature and humidity of

the local area were calculated based on the data when checking the environmental sensitivity of the model, and the effects of the change of weather pattern on the fungal growth rate, decomposition rate and wood decomposition were simulated. Since climate change involves long-term dynamic processes, the interaction between fungi needs to be considered. The simulation object was discussed and analyzed with two competing fungi.

First, two competing fungi, *Phellinus hartigii* and *Phlebia acerina*, were selected. At the same time, enter the corresponding temperature and humidity data in *MATLAB* to calculate the characteristics of the fungus in the current competitive situation. Suppose that after 10 years, the climate warms, the global average temperature increases by 0.2, and the humidity increases by about 10%. The original average temperature and humidity data were added and processed to simulate the weather pattern after 10 years. The characteristics of fungi were calculated again to compare the difference with that of 10 years ago. (In order to highlight long-term changes in atmospheric temperature, fluctuations in temperature are not taken into account here.) The simulation results are shown in the figure below:

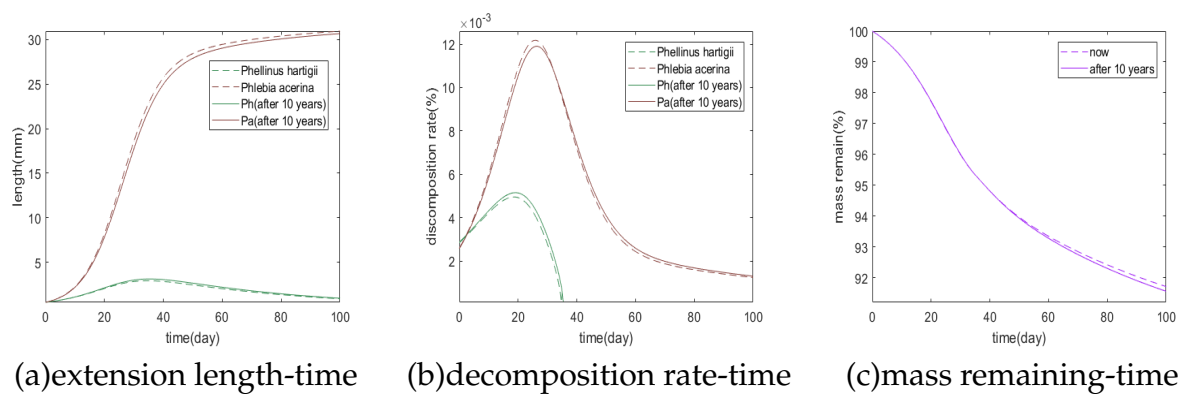


Figure 7: The dynamic characteristics of fungi before and after climate change of 10 year

As can be seen from the above chart, the effect of weather patterns on fungal growth is small because the change of weather patterns before and after 10 years is not drastic. Therefore, there was no significant difference in the growth rate, decomposition rate and the degree of wood decomposition between the two fungi in the competition condition after 10 years. After 10 years, because of the increase of temperature and humidity, the growth rate and decomposition rate of fungi were slightly higher than that of 10 years ago, and the degree of wood decomposition was also slightly increased.

Through the above simulation process, we found that when the fungi were in a competitive relationship, the fungi with strong competitiveness and fast growth could not adapt well to the drastic changes in the environment, and the number of fungi decreased rapidly. However, fungi with weak competitiveness and slow growth can adapt to drastic changes in the environment, and their growth is inhibited but not significantly reduced.

6 Model 2: comparative advantage prediction model

6.1 Definitions of comparative advantages and disadvantages

In order to predict the relative strengths and weaknesses of each species and possible combinations of species, a definition of the relative strengths and weaknesses needs to be determined first.

⇒ The relative advantages of individual species

According to the above statement and in combination with formula (12), it can be seen that there is a normal distribution relationship between the elongation of fungi and the ambient temperature and humidity, and the growth rate of fungi is greatly affected by the fluctuation of environmental factors. When there is a big gap between the temperature or humidity of the environment and the suitable growth temperature and humidity of the fungus, the fungus will stop growing and lose its advantage. Therefore, when the temperature niche width T_i^w and humidity niche width M_i^w were larger, a fungus could maintain a relative growth advantage in the weather. Therefore, environmental tolerance of fungi F_i can be defined as a measure of relative advantages or disadvantages of fungi.

$$F_i = T_i^w \times M_i^w \quad (15)$$

⇒ The relative advantages of species combinations

According to the optimum temperature and temperature niche width of a single species, the minimum adaptive temperature T_i^{min} and the maximum adaptive temperature T_i^{Max} of various fungi can be calculated, as shown:

$$T_i^{min} = T_i^* - \frac{1}{2}T_i^w \quad (16)$$

Where, T_i^* represents the optimal temperature of fungi i .

Similarly, the lowest adaptive humidity M_i^{min} and the highest adaptive humidity M_i^{Max} of various fungi can be obtained. From this, the range of environmental conditions in which each species can survive is calculated.

For fungi in a combination, there are maxima and minima for temperature and humidity. The advantage of population combinations to form a community is that in the face of extreme weather, even if a population within the community dies, there will still be other populations to maintain the stability of the community. Therefore, the minimum adaptive temperature of each group can be used to estimate the minimum temperature that the combination can resist, and the maximum adaptive temperature can be used to estimate the maximum temperature that the combination can resist. Similarly, minimum and maximum humidity can be estimated in the same way. Specifically expressed as:

$$\begin{cases} T^{min} = \min(T_1^{min}, T_2^{min}, \dots, T_n^{min}) \\ T^{max} = \max(T_1^{max}, T_2^{max}, \dots, T_n^{max}) \\ M^{min} = \min(H_1^{min}, H_2^{min}, \dots, H_n^{min}) \\ M^{max} = \max(H_1^{max}, H_2^{max}, \dots, H_n^{max}) \end{cases} \quad (17)$$

Therefore, the overall fitness of species combination F^{ALL} can be expressed as

$$F^{All} = (T^{max} - T^{min}) \times (M^{max} - M^{min}) \quad (18)$$

In summary, the relative advantages and disadvantages can be predicted by calculating the environmental fitness F_i of individual species or the overall fitness F^{ALL} of species combinations. The greater the environmental fitness, the greater the relative advantage; On the contrary, the smaller the environmental fitness is, the more difficult it is to adapt to the changes of the environment, thus showing a relative disadvantage.

6.2 forecast relative advantages and disadvantages in different climates

First, select 4 species of fungus. Because it is necessary to predict the relative advantages and disadvantages of fungi in the environment, the long-term existence of fungi and the influence of environmental factors on fungi should be ensured in the simulation process. Therefore, 4 of fungi should be selected for cooperation. The four fungi selected were *Armillaria gallica*, *Hyphoderma setigerum*, *Phellinus robiniae*, and *Schizophyllum commune*. Based on the relevant data, the environmental fitness of each fungus or species combination was calculated.

On the basis of the environmental fitness, the 4 species of fungi alone and the 6 species in pairs were predicted under different climatic conditions. It is known that fungi with high environmental adaptability grow stably, and the fluctuation of environmental factors has little effect on the decomposition of wood. Fungi with low environmental adaptability are greatly affected by environmental factors, so the decomposition rate fluctuates greatly when the environment changes. Therefore, we predicted that the higher the environmental fitness was, the less the degree of wood decomposition fluctuated in different environments, that is, the less the variance of the remaining wood mass was.

Using the simulation method mentioned above, 10 scenarios were put into the 5 cases of arid, semi-arid, temperate, arboreal and tropical rain forest for testing to determine whether the prediction was accurate. The variance of the remaining wood mass content in different environments is used as an indicator to judge whether the prediction results are accurate. The results are shown in the following table:

Table : Table of comparative advantage prediction and test results in different climates

| Species Climate | Ag | Hs | Pr | Sc | Ag-Hs | Ag-Pr | Ag-Sc | Hs-Pr | Hs-Sc | Pr-Sc |
|---------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Environmental fitness | 74.347 | 33.386 | 18.819 | 42.46 | 78.868 | 22.62 | 49.98 | 72.185 | 53.12 | 36.706 |
| Predict Advantage Ranking | 1 | 3 | 4 | 2 | 1 | 6 | 4 | 2 | 3 | 5 |
| Arid | 98.737 | 91.971 | 94.891 | 91.807 | 95.070 | 91.785 | 93.936 | 92.358 | 91.915 | 93.770 |
| Semi-arid | 98.690 | 92.171 | 91.731 | 92.263 | 94.783 | 96.694 | 94.833 | 93.132 | 92.597 | 95.678 |
| Temperate | 98.519 | 93.898 | 98.981 | 93.546 | 94.616 | 94.475 | 93.856 | 92.207 | 91.969 | 93.886 |
| Arboreal | 99.042 | 92.232 | 92.779 | 92.535 | 94.856 | 93.002 | 93.503 | 92.331 | 91.566 | 93.286 |
| Tropical rain forests | 98.547 | 92.393 | 89.835 | 92.173 | 94.617 | 96.602 | 94.473 | 92.833 | 92.184 | 95.270 |
| SD | 0.187 | 0.696 | 3.129 | 0.589 | 0.169 | 1.941 | 0.473 | 0.351 | 0.339 | 0.926 |
| Actual Advantage Ranking | 1 | 3 | 4 | 2 | 1 | 6 | 4 | 2 | 3 | 5 |

Where, SD represents the variance of wood residual mass under five climatic conditions.

It can be seen from the above table that the relative advantages of species predicted based on environmental fitness are completely consistent with the detection results. It shows that the forecast index is reliable and effective.

At the same time, we selected two environments where the humidity difference

between drought and tropical rain forest was very significant to analyze the relative advantages and disadvantages of each species and species combination.

First, when a single species is present, the results are shown in the figure below:

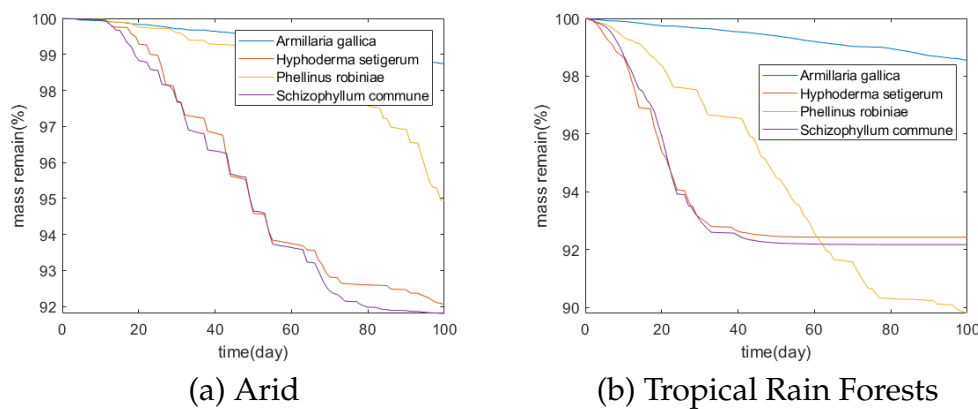


Figure 8: The remaining mass of wood under different climatic conditions when the species is alone

Combined with Figure (8), when the species existed alone, from drought to tropical rain forest, because the environmental fitness of fungus *Ag* represented by the blue curve was 74.347 at most and was least affected by environmental changes, the decomposed wood function was relatively stable, and the remaining relative mass was maintained at about 98.4%. Although the decomposition speed is slow, but can decompose for a long time, the most obvious relative advantage. On the contrary, fungi represented by the yellow curve had the minimum environmental adaptability of *Pr* of 18.819, which was greatly affected by environmental fluctuations. From arid environment to tropical rain forest, the remaining relative mass changed from 89.4% to 94.9%, and the difference of decomposed wood was obvious, which could be considered as inferior bacteria.

From another perspective, although the final decomposition of fungal *Pr* fluctuates widely, compared with fungal *Ag*, fungal *Pr* can always decompose more wood quality than fungal *Ag* no matter how the environment changes. From this perspective, it can be considered that fungal *Pr* and fungal *Ag* are the dominant bacteria.

It is worth noting that under drought conditions, the humidity is low and the temperature difference between day and night is large. When the fluctuation of environmental factors exceeds the ecological niche of fungi, the decomposition of fungi can be considered to be almost stopped, so there will be stepped fluctuation and large fluctuation in the figure. In the tropical rain forest, the humidity is high, the temperature is relatively balanced, and the graph fluctuations are small.

In the presence of species combinations, the results are as follows:

Ag – *Hs* combination of overall fitness is about 78.868, is affected by the environmental variation minimum in the figure, the wood quality variance minimum remaining, 0.169, and *Ag* – *Pr* combination, of all the combination of overall fitness minimum 22.62, the environmental variation has the greatest impact in the figure, timber quality variance minimum remaining, 1.941, so relative to *Ag* – *Hs* combination, disadvantage is obvious.

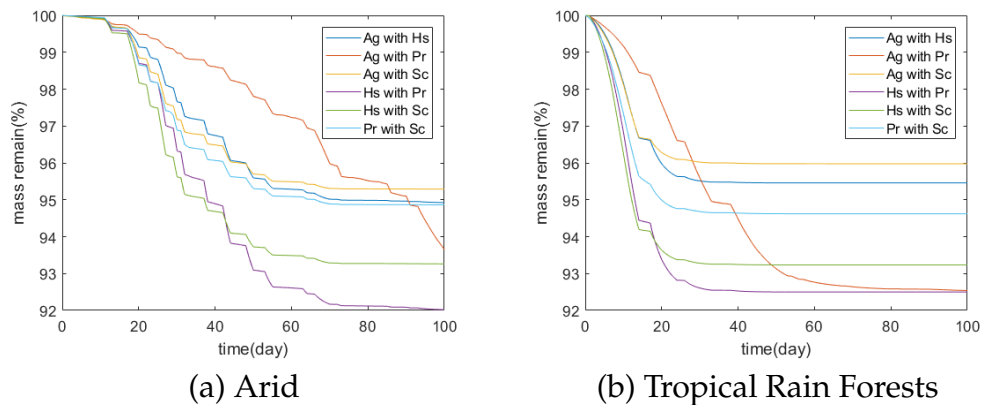


Figure 9: The residual mass of wood under different climatic conditions in species combinations

7 the description of biodiversity

7.1 The impact of biodiversity on overall efficiency

Four fungi, *Armillaria sinapina*, *Armillaria gallica*, *Phlebia acerina* and *Laetiporus conifericola*, were assumed to exist in the environment, and the fungi *As* and *Ag* were homologous. According to the data in Table 1 in the appendix, the decomposition rates of the four fungi and the total decomposition rates of the four fungi acting together were respectively calculated through the above method, so as to obtain the remaining mass of wood after decomposition in each case, as shown in the figure below:

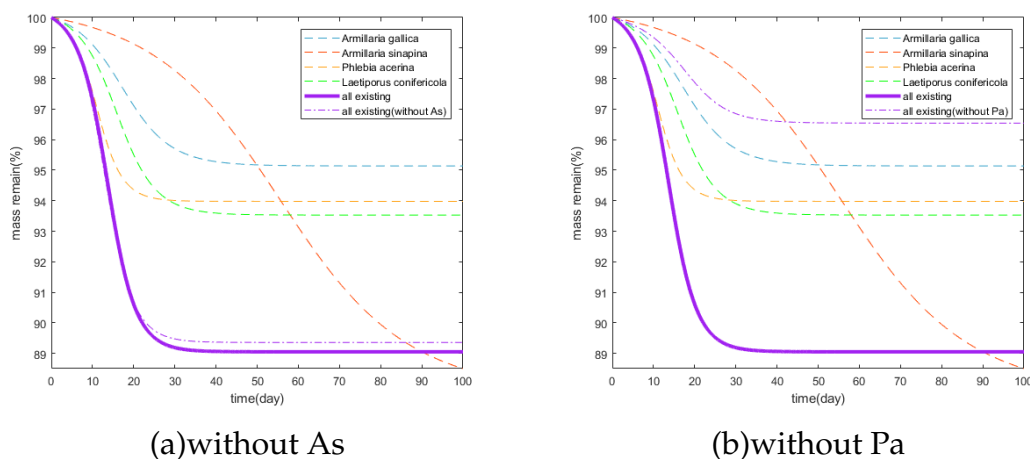


Figure 10: The impact of biodiversity on overall efficiency

In the case of no species death by figure (10), *As*, *Ag*, *Pa* and *Lc* four kinds of fungi exist alone when their total decomposition rate of 4.8%, 15.0%, 6.1%, 6.5%. The total decomposition rate was 11.0%. When the four fungi coexisted, which was higher than that when most fungi existed alone.

As shown in the above 10(a), literature showed that fungus *As* and *Ag* for homologous fungus, when a region within the four fungi *As*, *Ag*, *Pa*, *Lc*, proportion of 25%, 25%, 25% and 25%, respectively. The overall efficiency of decomposition of wood is 11.1%. When only three fungi *Ag*, *Pa* and *Lc* were left in a region, accounting for 50%,

25% and 25%, respectively. The overall efficiency of woody decomposition was 10.8%, which showed no significant difference compared with the previous ones. This indicates that Ag can be replaced by As. In the presence of the four fungi, if Ag becomes extinct due to environmental mutation, the substitution of As for Ag will not have a significant impact on the decomposition efficiency of the ecosystem. Therefore, it can be concluded that biodiversity is the guarantee for the stability of the decomposition efficiency of the ecosystem.

As shown in Figure 10(b), when fungal Pa disappeared and the remaining three fungi Ag, As and LC accounted for 33%, 33% and 33%, respectively. The balance of the system was broken and the overall efficiency of wood decomposition was reduced to 3.2%, which was significantly different from the original. Therefore, for distant relatives such as Pa, the presence or absence of such species will have a great impact on the decomposition efficiency of the ecosystem. From another perspective, it can be shown that biodiversity is the guarantee for the stability of the decomposition efficiency of the ecosystem.

7.2 The importance and role of predicting biodiversity

This process demonstrates the role of the overall environmental fitness of the system F^{All} in maintaining system balance. There is a certain relationship between the environmental fitness of fungi and the population number of fungi. With the increase of the population number, the probability of the occurrence of fungi with strong tolerance to extreme temperature and humidity among different species will also increase. Therefore, using the data of 30 species of fungi in the appendix table 1, Monte Carlo simulation algorithm was adopted to simulate the environmental fitness or the overall environmental fitness of 1 species, 2 species and 3 species of fungi as a 1 system. After simulating 8000 times, the result is shown in the figure below

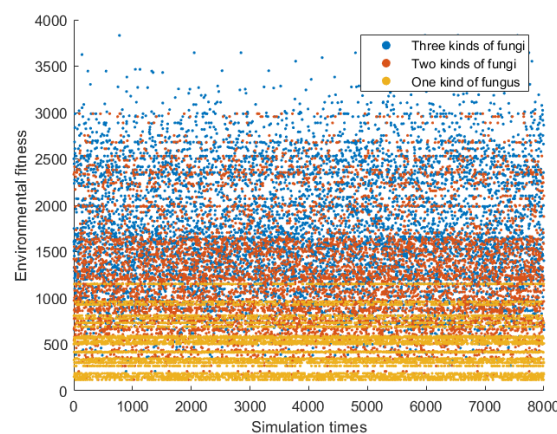


Figure 11: Monte Carlo simulation results

It can be intuitively found from the scatter plot that the environmental fitness of a fungus after simulation is basically less than 1000, with an average value of 484.056. However, most of the simulated results of the two fungi were below 1600, with an average value of 1228.944. The environmental fitness obtained by using the three fungi was distributed below 3000, with an average value of 1717.305. With the increase of fungal species from 1 species to 3 species, environmental fitness increased gradually.

In conclusion, biodiversity can maintain the stability of the system, improve the overall efficiency of decomposition of the system, and enhance the overall adaptability of the system to resist environmental changes.

Since fungi that are better able to adapt to a wider range of moisture conditions tend to decompose wood more slowly, it can be inferred that fungi that decompose more slowly have a better ability to adapt to changes in ambient humidity. So if our model is reliable, it should be able to reflect this correctly.

We selected two species of fungi, one of which decomposes rapidly and has strong environmental adaptability, and the other of which decomposes slowly but has strong environmental adaptability. If we culture these two fungi separately under the same environmental conditions, according to our model, we can get the culture results under such conditions, including the growth rate, decomposition and so on. If we change the environmental conditions and increase the humidity, the results of the culture will change accordingly.

The calculation results of the model are as follows

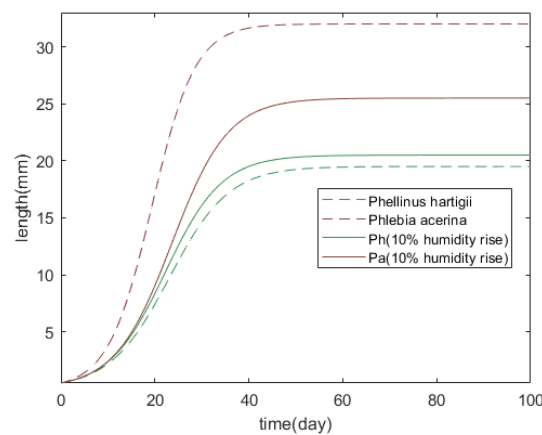


Figure 12

As can be seen from the dotted line, *Phlebia acerina* grew significantly faster than *Pellinus hartigii* when the two fungi were cultured in the same environment before changing humidity. The growth of *Phlebia Acerina* was significantly inhibited and slowed down, and the mycelium length changed from 32.2mm to 25.6mm, while the growth of *Phellinus hartigii* was not inhibited or even promoted to a certain extent, and the mycelium length changed from 19.2mm to 21.1mm. It can be seen that the difference in growth rate between *Phlebia Acerina* and *Pellinus Hartigii* becomes very small after changing humidity, and the difference in final mycelial length between the two is also reduced. These results indicate that our model is reliable and are consistent with the fact that fungi that decompose more slowly have a better ability to adapt to changes in environmental humidity.

8 Strengths and Weaknesses

- Strengths

1. Three interactions among fungi was discussed and the dynamics of succession among microbial communities was revealed .

2. Two characteristics of moisture tolerance and extension rate were used to fit the decomposition rate of fungi, and the fitting effect was good, realizing the prediction of the decomposition rate of fungi through these two characteristics.
 3. The model was sensitive to climate fluctuations, and the changes of the results are in line with the reality, which reflects the accuracy and reliability of the model.
- Weaknesses
1. Less fungal species were selected in the simulation.
 2. The effect of mycelium density on fungal growth was not considered.

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Memo

Fungi in the ecological system

The carbon cycle refers to the phenomenon that carbon elements exchange in the biosphere, lithosphere, hydrosphere and atmosphere on the earth, and continue to cycle with the movement of the earth. It is an important process of the movement of life on the earth. The biosphere carbon cycle is an active part of carbon exchange in the geochemical cycle, in which the decomposition of plant materials and wood fibers by microbial and fungal communities is the key process of the biosphere carbon cycle.

A fungus is a member of a eukaryotic organism (a cell whose nucleus is enclosed in a nuclear membrane). Common fungi in nature are yeasts, molds and mushrooms. Fungal respiration is a crucial factor in the carbon cycle of the biosphere. Previous studies have not clearly identified factors that correlate with fungi 'ability to break down carbon. Fortunately, recent studies have shown that mycelial elongation and moisture tolerance of fungi are highly correlated with decomposition rates. Through the modeling and fitting process of our team, it was found that the fitting effect of mycelium elongation, moisture tolerance and decomposition rate was very perfect, reaching a fitting degree of nearly 85%. This fully shows that in nature, the ability of fungi to decompose carbon is mainly affected by elongation and moisture tolerance.

The actual elongation of fungi is affected by the interaction between fungi. Therefore, a differential equation model of the growth rate of fungi is established to simulate the interaction between fungi. In an ecosystem, interactions between fungi can be divided into three types: competition, cooperation and one-way promotion. Through simulation, we can find that in the short term, the growth rate and decomposition rate of the three cases are all increased, and the decomposition effect of the humus is enhanced. However, the long-term trend is not the same. When the fungi compete with each other, the fungi with high competitive ranking significantly inhibit the fungi with low competitive ranking, resulting in negative growth until death. In the cooperative relationship, the fungi grow steadily and continuously to reach the environmental capacity, and the total decomposition rate is higher than that of the fungi alone. In the unidirectional promotive relationship, the promotive fungi were gradually killed by the competitive effects of the competitive fungi, and the growth rate of the promotive fungi decreased gradually due to the loss of the promotive fungi.

The actual elongation rate of the fungus is also closely related to the environment. The effects of environmental factors, including temperature and humidity, on the growth rate of fungi were considered on the basis of the interaction between fungi. When the environment fluctuates rapidly, the growth rate of fungi also changes significantly, leading to the change of decomposition rate. Due to the slow change of atmosphere, the decomposition rate of fungi will not be significantly affected in the short term.

In an ecosystem, each species has its own environmental niche width, through which the environmental niche width can be calculated to predict the relative advantages and disadvantages of a species. For the existing species combination, the overall fitness of the combination can be obtained according to the environmental fitness of each species in the combination, which can also be used to predict the relative advantages and disadvantages.

When environmental factors change to different degrees, if the degree of change is beyond the ecological niche range of the fungus, the fungus will die and the population

will disappear. The balance of the system is disturbed, and the rest of the population is also affected, resulting in a decrease in the overall efficiency of system decomposition. However, if there is a lot of biodiversity in the system and there is a "substitute" for the population, when the population disappears, the number of "substitutes" increases to compensate for its position, and the overall efficiency of the system does not change significantly. Monte-Carlo simulations of fungal biodiversity showed that when the number of fungal populations increased, the overall system became more adaptable to the environment and more resilient to risk.

In conclusion, biodiversity can maintain the stability of the system, improve the overall efficiency of decomposition of the system, and enhance the overall adaptability of the system to resist environmental changes.