Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
A		**2112334**

Decomposition of fungal communities and their effects on ecosystems

Summary

As an indispensable decomposer in nature, fungi play an important role in the carbon cycle of ecosystems. The purpose of this article is to establish a fungal decomposition model, and consider the interaction between a variety of fungi and the impact of the environment on the decomposition efficiency, and then explore the role of fungal diversity on the ecosystem. To this end, we build a **fungal decomposition model** and an **environmental impact model**.

The fungus decomposition model establishes a negative exponential equation of wood quality attenuation. Then, based on the research results of Nicky Lustenhouwera and others, the expression of fungal decomposition rate is determined. The model mainly considers the moisture tolerance of fungi, the number and the growth rate of fungi. The growth rate refers to the **logistics retarded growth model**. Our experimental results show that the intrinsic growth rate of fungi has a greater impact on wood decomposition rate than moisture tolerance; at the same time, in a multi-species competition environment, wood decomposition efficiency may be lower than that in a single-species decomposition environment. The result of competition is often that fungi with a higher competitive ranking reach the environmental capacity, and fungi with a lower ranking die out.

The environmental impact model mainly discusses the impact of factors including **temperature**, **pH** and **moisture level** on the multi-species decomposition model. **The relative distance between environmental indicators and the optimum condition of the fungus is used to establish the equation of the environmental capacity of fungi under environmental changes.** Consider changes in the relative merits of fungi in various environments. It can be found that the environment will change the decomposition efficiency of fungi, but will not affect the relative competitive advantage between fungi, which is mainly determined by the intrinsic growth rate and moisture tolerance.

Then use the above model to discuss the influence of fungi species diversity. Fungi that assist each other can increase the efficiency of decomposition, and competing fungi will reduce the efficiency due to competition for resources. Experiments show that when the environmental indicators begin to fluctuate, when there are multiple fungi, the decomposition efficiency fluctuates little, which is 52.4% under the condition of a fungus. This proves that biodiversity plays an important role in maintaining the stability of the ecological environment.

Finally, the advantages and disadvantages of the model and sensitivity analysis are carried out to prove the stability of the model.

Keywords: *fungal decomposition* ; *moisture tolerance* ; *logistics growth model* ; *species diversity* ; *ecosystem stability* ; *population competition*

Contents

1 Introduction

1.1 Literature Review

The carbon cycle is one of the three important cycles in nature, and the decomposition of organic matter is an indispensable step in the carbon cycle. The decomposition of litter is inseparable from the support of microorganisms. Microorganisms complete the decomposition of litter by secreting enzymes, and fungi can secrete cellulase that other microorganisms cannot produce. Therefore, fungi occupies a higher position in litter decomposition. It can play a role in maintaining forest ecosystems, improving forest fertility, and promoting forest energy cycle.

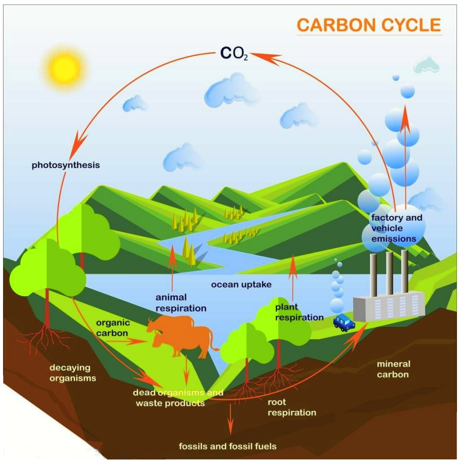


Figure 1: Carbon cycle[2]

Different fungi have different decomposition rates. Studies have shown that the decomposition rate of fungi is related to the growth rate and moisture resistance of fungi. According to the literature [1], the decomposition rate of fungi is approximately proportional to the growth rate, and the logarithm of the decomposition rate is approximately proportional to the moisture resistance.

When there are multiple types of fungi in the environment, there is an interaction between them, and the decomposition rate of fungi will not be equal to the simple addition of the decomposition rates of each fungus. Differences in environment and biodiversity will affect the decomposition rate of fungi.

1.2 Restatement of the Tasks

In order to clarify our tasks, we simplify our team' s 3 tasks below:

Task 1 Establish a model to describe the decomposition rate of litter in the presence of multiple fungi. Analyze the dynamic characteristics of the interaction between different fungi in short and long time. Perform sensitivity analysis to rapid environmental changes.

Task 2 Establish the model of the influence of environmental changes on the decomposition rate of fungi, evaluate the relative advantages and disadvantages of different species or combinations of species in the five environments of arid, semi-arid, temperate, tree and tropical rainforest, and determine the influence of the overall atmospheric transformation trend on fungal decomposition efficiency.

Task 3 Describe the impact of fungal diversity on the decomposition rate, and predict the role of biodiversity when the environment changes.

1.3 Our work

Using a database composed of 37 fungi characteristics[3], a kinetic model of fungal decomposition during litter decay was established. Considering a single strain, construct the Negative exponential loss equation for wood, Fungal decomposition rate equation and Fungus number logistics model. When considering multi-strains, the interaction between fungi is considered, and a fungal population competition model is proposed, and the degree of interactions between fungal species is measured by the ratio of fungal competitive ranking to discuss the short-term and long-term effects of multi-strain interactions. Secondly, establish an environmental impact model on the decomposition rate of fungi. Environmental variables indirectly affect the decomposition rate by affecting the environmental capacity of fungi. When the environment (temperature, pH, moisture level) changes, consider the sensitivity of the model to fluctuations. And under five typical climatic conditions (including arid, semi-arid, temperate, forest and tropical), the relative competitive advantages of different species were compared. Finally, we discussed the importance of biodiversity.

In general, our problem solving process is shown in Figure 2.

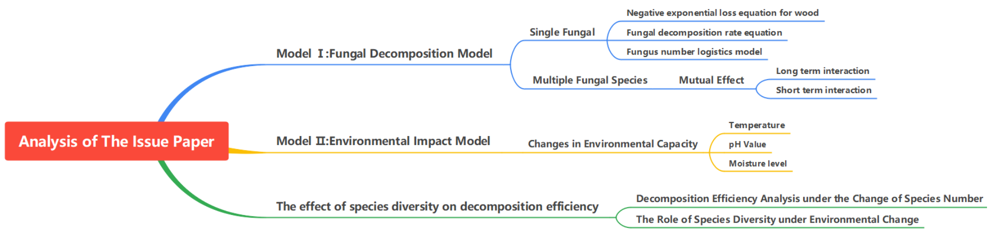


Figure 2: problem solving process

2 Assumption and Notation

2.1 Assumption

To simplify the problem, we make the following basic assumptions, each of which is properly justified.

- A variety of fungal properties have an impact on the decomposition rate. In order to simplify the analysis, this model only considers the effects of fungal growth rate and moisture resistance on the fungal decomposition rate.
- The interaction between fungi is only reflected in the impact on the number of various fungi.
- hyphal extension rate can be used to measure the intrinsic rate of fungal growth.
- The environmental capacity of fungi is only affected by temperature, pH, and moisture level.
- The maximum environmental capacity of various fungi in the most suitable environment is the same, denoted by N.
- All data in the article are accurate and reliable.

2.2 Notation

Notation that we use in the model are shown in the following table.

symbols	definition
$M(t)$	At time t, the total amount of litter
M_0	The total amount of litter at the initial moment
K_i	Decomposition rate of the i-th fungus
x_i	The number of the i-th fungus
G_i	Growth rate of the i-th fungus
N_i	Environmental capacity of the i-th fungus
r_i	The intrinsic growth rate of the i-th fungus
σ_{ij}	The degree of influence of the i-th fungus on the j-th fungus
l_i	Moisture tolerance of the i-th fungus

3 Model I : Fungus decomposition model

As a key factor in the decomposition of decaying substances, fungi play an important role in the carbon cycle in nature. Recently, studies have shown that some fungal traits have a significant impact on the decomposition rate [1]. In this regard, we consider the two most important characteristics: the growth rate of the fungus and the moisture tolerance of the fungus, and construct a fungal decomposition model in the form of a negative exponent [4].

3.1 Single fungus decomposition model

3.1.1 Equation of the attenuation of organic matter

Use M to measure the total mass or energy of organic matter in a fixed area. The decomposition of fungi makes M gradually attenuate. We use a semi-exponential model to express this functional relationship.

$$lnM = -\int_0^t k\mathrm{d}t + lnM_0 \tag{1}$$

Simplify and get

$$ln\,(\frac{M}{M_0}) = -\int_0^t k\mathrm{d}t \tag{2}$$

$$\frac{M}{M_0} = e^{-\int_0^t k\mathrm{d}t} \tag{3}$$

Among them, M_0 represents the initial mass, and K represents the decomposition rate of the fungus to the litter. The specific expression will be obtained later.

3.1.2 Fungal decomposition rate

The decomposition of organic matter provides nutrients for the growth and reproduction of fungi, so the decomposition rate of organic matter is closely related to the growth of fungi. The increase in the number of fungi will accelerate the decay of organic matter. Similarly, according to the research results of Nicky Lustenhouwer et al., the trait of biological moisture tolerance is also related to the decomposition rate. Under the conditions of suitable environment and abundant material, the decomposition rate of fungi (the rate of mass loss of organic matter) is proportional to the number and growth rate of fungi, and the logarithm of the decomposition rate is directly proportional to the moisture tolerance of the fungus.[1]

Therefore, the expression of fungal decomposition rate can be expressed as equation (4):

$$K(t) = \theta \cdot x(t) \cdot G(t) \cdot e^{l} \tag{4}$$

Among them, θ represents a constant coefficient, $x(t)$ represents the number of the fungus at time t, $G(t)$ represents the growth rate of the fungus at time t, and l represents the moisture tolerance of the fungus.

When there is only one fungus involved in the degradation process in the environment, we use the logistic model to describe the change process of the population $x(t)$.

$$G(t) = \frac{\mathrm{d}x(t)}{\mathrm{d}t} = \gamma x(1 - \frac{x}{N}) \tag{5}$$

Among them, γ is the intrinsic growth rate of the population, and N is the Maximum environmental capacity. It is easy to get, when $x = N$ is a stable equilibrium point, that is, when $t \to +\infty$, $x(t) \to N$.

3.1.3 Discussion of results

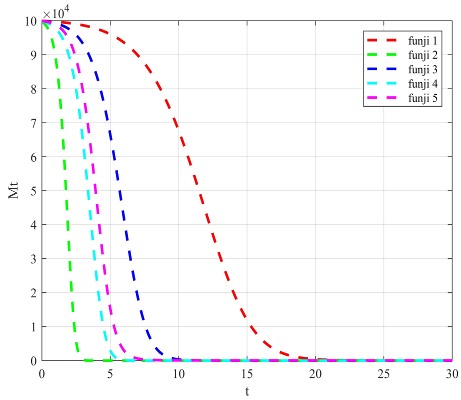
The selected fungi data are shown in Table 1:

Table 1: Parameters of the selected fungus

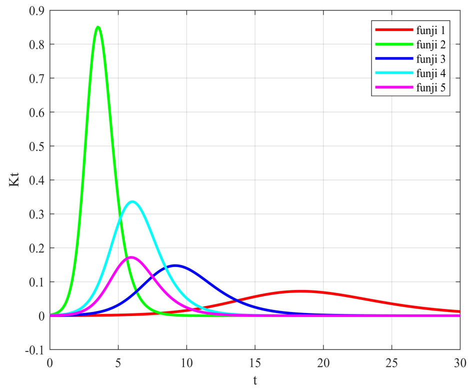
No.	fungus name	γ	moisture tolerance	colour
1	Armillaria_gallica_FP102531_C6D	0.25	-0.25026	red
2	Mycoacia_meridionalis_FP150352_C4E	1.3	0.569495	green
3	Armillaria_tabescens_FP102622_A3C	0.5	-0.22656	blue
4	Armillaria_gallica_SH1_A4A	0.76	0.177229	blue-green
5	Xylobolus_subpileatus_FP102567_A11A	0.77	-0.5068	fuchsia

According to Model I, using the data in Table 1, the mass change curve (as shown in Figure 3a) and the decomposition rate change curve (as shown in Figure 3b) of single fungi species decomposing litter can be obtained.

In Figure 3a, the intrinsic growth rate of fungi No. 1 (red line in the figure) is the slowest, and the moisture tolerance ranks second. No. 2 fungi (the green line in the figure) has the lowest moisture tolerance among the five strains, but the intrinsic growth rate is the highest. It



(a) Changes in the quality of litter over time



(b) Changes in the decomposition rate of fungi over time

Figure 3: Curve describing the decomposition of a single fungus

can be seen from Figure 3a that the green line is the fastest of the five curves to reach zero. Therefore, it can be concluded that the inherent growth rate of fungi has a greater impact on the rate of wood decomposition than moisture tolerance.

Figure 3b shows the change of the decomposition rate of fungi over time, which can be regarded as the change of the slope of the curve in Figure 3a over time. Although the fungi are different and the maximum decomposition rate is different, the overall trend of the decomposition rate is the same. The decomposition rate of fungi gradually increases and then gradually decreases. The reason is that in the initial stage of decomposition, the total amount of litter is sufficient to provide sufficient nutrients for fungi. The number of fungi gradually increases, so the decomposition rate of litter gradually changes. When the decomposition rate reaches the maximum, the litter cannot meet the funguss demand for organic matter, and the growth rate of fungi begins to slow down, so the fungal decomposition rate gradually decreases. When the litter is completely decomposed, the number of fungi remains stable and the fungal decomposition rate is zero.

3.2 Multiple fungal competition model

3.2.1 Model establishment

When there are n species of fungi in the same area to decompose organic matter, The reduction in the total amount of organic matter is the sum of the decomposition effects of various fungi on organic matter, it can be known from the equation (1)

$$lnM = -\sum_{i=1}^{n} \left(\int_0^t k_i \mathrm{d}t \right) + lnM_0 \tag{6}$$

Simplify and get a variety of fungal decomposition equation (8).

$$ln\,(\frac{M}{M_0}) = -\sum_{i=1}^{n}\left(\int_0^t k_i \mathrm{d}t\right) \tag{7}$$

$$\frac{M}{M_0} = e^{-\sum_{i=1}^{n}\left(\int_0^t k_i \mathrm{d}t\right)} \tag{8}$$

The decomposition rate of fungi still satisfies the equation (4).

Organic matter is a common resource demanded by different fungi. In order to compete for limited resources, the growth model of a single species number is converted to a multi-species competition model. Here, the competition between two species is taken as an example. According to the population competition model, we can see

$$G_i(t) = \frac{\mathrm{d}x_i(t)}{\mathrm{d}t} = \gamma_i x_i\left(1 - \frac{x_i}{N_i} - \sigma_{ij}\frac{x_j}{N_j}\right) \tag{9}$$

$$G_j(t) = \frac{\mathrm{d}x_j(t)}{\mathrm{d}t} = \gamma_j x_j\left(1 - \frac{x_j}{N_j} - \sigma_{ji}\frac{x_i}{N_i}\right) \tag{10}$$

It should be noted that N_i represents the maximum environmental capacity of the i-th fungus, which is a function of environmental temperature, pH, and dryness and wetness. σ_{ij} represents the effect of strain i on strain j The degree is expressed by the ratio of the competitive ranking of the two strains, as shown in equation (11).

$$\sigma_{ij} = \frac{ranking_i}{ranking_j} \tag{11}$$

Competitive ranking is a measure of the ability of a fungus to outperform other fungi in a series of paired tests conducted under similar conditions. The specific value has been calculated by Daniel S. Maynard et al [3].

3.2.2 Discussion of results

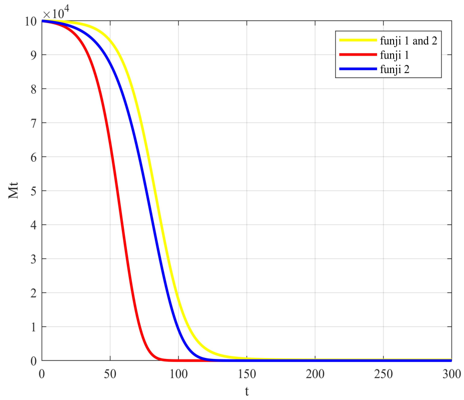
Based on a large number of experiments, the two fungi shown in Table 2 were analyzed to illustrate the influence of the interaction of the two species of fungi on the decomposition of wood.

Table 2: Parameters of the selected fungus

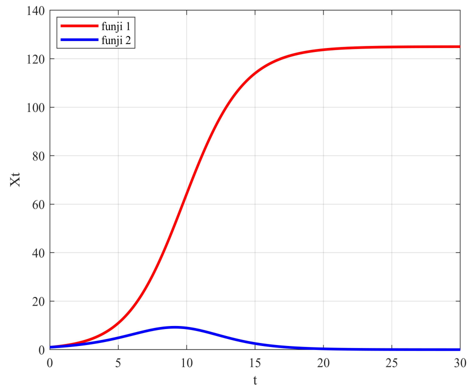
No.	fungus name	γ	moisture resistance	colour
1	Armillaria_gallica_EL8_A6F	0.5	-0.22656	red
2	Armillaria_tabescens_FP102622_A3C	0.35	-0.07168	blue

In experiment ,$\theta = 0.001$, $N = 125$, $M_0 = 10^5$

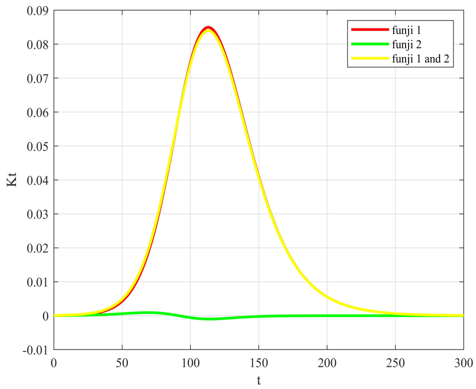
The above modeling process can be realized by using matlab. Under the joint action of the two groups of fungi, the total amount of wood changes over time (Figure 4a), the number of



(a) The total amount of wood changes over time



(b) Changes in the number of two fungi over time



(c) Changes in the decomposition rate of two fungi with time

Figure 4: Curve of decomposition of two fungi of experiment 1

two fungi changes over time (Figure 4b), and the decomposition rate of the two fungi changes over time (Figure 4c).

It can be seen from the three curves of Figure 4a that the time relationship required for the complete decomposition of wood in the three cases is: $t_{yellow} > t_{blue} > t_{red}$. This shows that under competitive conditions, the two fungi inhibit each other, resulting in slower wood decomposition, so when the two fungi coexist, it will take longer for the wood to completely decompose.

Through the competition model of multiple strains, the number changes of the two strains can be predicted as shown in Figure 4b. As compared with No. 2 fungi, the competitive ranking of No. 1 fungi is higher, so $\sigma_{21} > \sigma_{12}$. Because the fixed growth rate of No. 1 fungi is faster, so under the same external conditions and without interference, the No. 1 fungi has stronger competitive ability and more advantages, it can reach the maximum capacity over time. However,due to the weak competitiveness of fungus No. 2, it increased at the beginning and then gradually decreased until it died out.

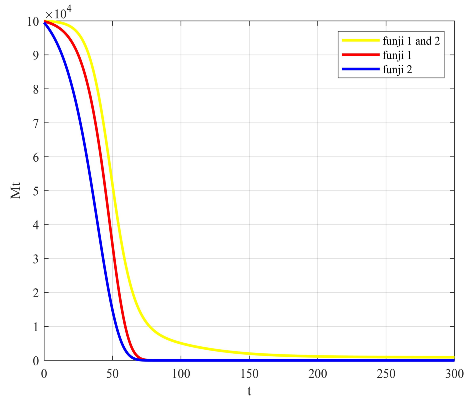
It can be seen from Figure 4c that the decomposition rate of No. 2 fungi was negative for a period of time in the short time, which indicates that the number of No. 2 fungi decreased during this period. When two populations exist at the same time, the actual decomposition rate of wood is the sum of the decomposition rates of the two fungi, so the decomposition rate of any fungus has no practical significance. However, as shown in Figure 4c, the total decomposition rate of the two fungi is always positive, which is consistent with reality.

It can be seen from Figure 4c that due to competition, No. 2 fungi is at a great disadvantage and the decomposition effect is not obvious in the long time. No. 1 fungi has an advantage in the competition, and its decomposition rate continues to increase. After the decomposition rate reaches its peak, on the one hand, because the wood is almost consumed, on the other hand, because the number of fungi is close to the environmental capacity, the decomposition rate decreases.

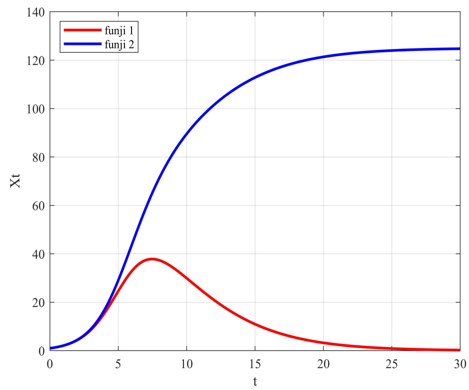
The analysis of two fungi in Table 3 shows the influence of moisture tolerance on the decomposition process of wood.

Table 3: Parameters of the selected fungus

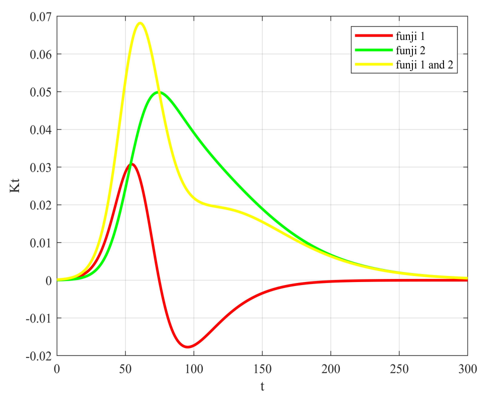
No.	fungus name	γ	moisture tolerance	colour
3	Armillaria_sinapina_PR9	0.77	0.221719	red
4	Xylobolus_subpileatus_FP102567_A11A	0.77	-0.5068	blue



(a) The total amount of wood changes over time



(b) Changes in the number of two fungi over time



(c) Changes in the decomposition rate of two fungi with time

Figure 5: Curve of decomposition of two fungi of experiment 2

The experimental results are shown in Figure 5

Figure 5a shows that in a competitive environment, the two fungi will take longer to decompose the same wood material than if they are decomposed separately.

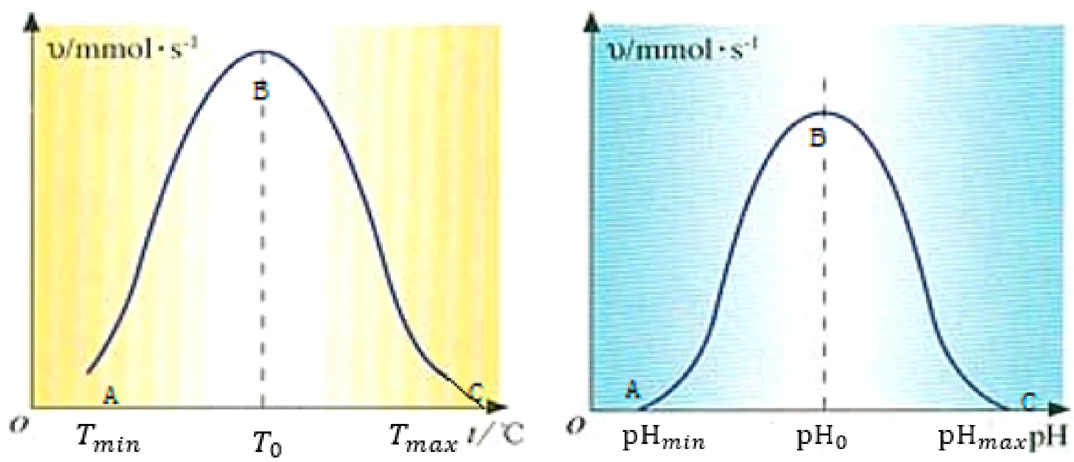
It can be seen from Table 3 that the growth rates of the two strains are the same, but the moisture tolerance of No. 4 fungi is stronger than that of No. 3 [3]. It can be seen from Figure 5b that the number of No. 4 fungi continues to rise and then stabilizes at a constant that is not zero. However, when the number of No. 3 fungi rises to a certain number, due to weaker competitiveness, the number immediately drops to 0. Therefore, a conclusion can be drawn. , Fungi with stronger moisture tolerance have stronger competitiveness.

It can be seen from figure 5c that in the short term, the decomposition rate of fungi No. 3 and No. 4 is basically the same. This is because the initial resources are abundant and the competition between the two fungi is not great. After a period of time, the decomposition rate of No. 3 fungi fell back to a negative number, indicating that the growth rate of No. 3 fungi was negative and the number began to decrease. This is because as the wood decomposes, resources become limited and the competition between the two fungi intensifies. , No. 4 fungi was in a dominant position in the competition, survived the competition, No. 3 fungi finally died.The total decomposition rate of the two fungi is always positive, which is the same as the reality.

4 Model II : Environmental influence on decomposition rate

Not only the traits of the fungus itself determine the rate of decomposition, but also the environment does.Studies have shown that the conditions for fungi to grow and reproduce on wood require moisture above the fiber saturation point. When the fungus enters the fiber structure, it can produce the corresponding cellulase to decompose the macromolecular organic matter in the tissue to obtain nutrients.[5]

When the environment changes, the enzyme activity of cellulose will be greatly affected. In order to simplify the analysis, only the influence of temperature, pH and moisture level on cellulase activity is considered. Different environmental conditions affect enzyme activity in different mechanisms. Excessive temperature and extreme acidic and alkaline environments can destroy the structure of enzymes, thereby inhibiting the growth of fungi. Too low temperature



(a) Enzyme activity changes with temperature (b) Enzyme activity changes with pH

Figure 6: The enzyme activity changes with temperature and pH

will also decrease the enzyme activity, resulting in a decrease in the rate of enzymatic reaction, thereby inhibiting the growth of fungi. Similarly, exceeding the maximum moisture level or below the minimum moisture level can also affect the growth of fungi.

The enzyme activity changes with temperature and pH as shown in the figure 6.

When the temperature is closer to the optimum temperature of the fungus, the pH is closer to the optimum pH, and the moisture level is closer to the optimum moisture level, the higher the enzyme activity and the higher the environmental capacity.

This model considers the effects of **temperature**, **pH** and **moisture levels** on the environmental capacity not in the most suitable environment, and then combines the population competition model in Model I to discuss the effects of changes in these factors on the decomposition rate of fungi.

4.1 Model establishment

Define the distance between temperature, pH and moisture level from the optimal conditions as equations (12) (13) (14)

$$D(T) = \begin{cases} \dfrac{T - T_0}{T_{max} - T_0} & \text{if } T > T_0, \\ \dfrac{T - T_0}{T_{min} - T_0} & \text{if } T < T_0, \\ 1 & \text{if } T < T_{min} \text{ or } T > T_{max}. \end{cases} \tag{12}$$

$$D(pH) = \begin{cases} \dfrac{pH - pH_0}{pH_{max} - pH_0} & \text{if } pH > pH_0, \\ \dfrac{pH - pH_0}{pH_{min} - pH_0} & \text{if } pH < pH_0, \\ 1 & \text{if } pH < pH_{min} \text{ or } pH > pH_{max}. \end{cases} \tag{13}$$

$$D(m) = \begin{cases} \dfrac{m - m_0}{m_{max} - m_0} & \text{if } m > m_0, \\ \dfrac{m - m_0}{m_{min} - m_0} & \text{if } m < m_0, \\ 1 & \text{if } m < m_{min} \text{ or } m > m_{max}. \end{cases} \tag{14}$$

Among them, T_0, pH_0, and m_0 respectively represent the optimum temperature, optimum ph and optimum moisture level of the fungus.

N_i represents the maximum environmental capacity of the i-th fungus, expressed by the equation

$$N_i = N(1 - D(T))^a \cdot (1 - D(PH))^b \cdot (1 - D(m))^c, 0 \leq D(T), D(pH), D(m) \leq 1 \tag{15}$$

a, b, c are the physical quantities used to measure the impact of these three factors on the environmental capacity.

The significance of the equation (15) is that when any of the three values is close to 1, that is, close to the extreme situation, the living environment of the fungus will deteriorate rapidly, resulting in a decline in environmental capacity. For example, if the ambient temperature is close to the maximum temperature T_{max}, even if the pH and moisture levels are in the optimal conditions, the environmental capacity is still low.

According to the equation (9) (10) and equation (15), changes in environmental factors will affect the growth rate of fungi and further affect the decomposition rate.

4.2 The influence of the environment on the interaction between fungi

4.2.1 The influence of climate (temperature)

"Climate change" is defined as: "After a considerable period of observation, the climate change caused by human activities directly or indirectly changing the composition of the global atmosphere in addition to natural climate change." Since the Industrial Revolution, human activities have led to a significant increase in carbon dioxide emissions, making the most significant manifestations of global climate change as the greenhouse effect and global warming. So this section will discuss the effect of increasing temperature on the decomposition of wood by fungi.

Under the condition of constant pH and moisture level, different temperatures are selected to simulate the competitive decomposition process with representative Armillaria_gallica_EL8_A6F and Armillaria_tabescens_FP102622_A3C. Explore the effects of rapid changes in temperature conditions.

Table 4: Parameters of the selected fungus

No.	fungus name	T_{min}	T_{max}	$T_{optimum}$	γ	moisture resistance
1	Armillaria_gallica_EL8_A6F	19.2	32.5	29.8	0.47	0.0718
2	Armillaria_tabescens_FP102622_A3C	15.1	33.3	27.6	0.22	0.22656

In the environment where Armillaria_gallica_EL8_A6F and Armillaria_tabescens_FP1026 22_A3C can survive, the temperature gradient is set to 20, 23, 26, 29, 32. At different temperatures, the time required for wood to completely decompose is shown in Figure 7

It can be seen from Figure 7 that under other suitable environmental conditions and the same conditions, as the temperature increases, the time required for the fungal assembly to completely decompose wood first decreases and then increases, which means that the decomposition efficiency of wood first increases and then decreases. The optimum temperatures of the two bacteria are 29.8°Cand 27.6°Crespectively. The optimum temperature $T_{optimum}$ under the combination of the two bacteria is between 27.5°Cand 28.0°C. As the temperature T rises, before the temperature T reaches $T_{optimum}$, the decomposition efficiency of the bacterial combination gradually increased. When reaching $T_{optimum}$, the decomposition efficiency is maximum. When the optimal temperature $T_{optimum}$ is exceeded, the decomposition efficiency of the bacterial combination decreases. Moreover, the higher the temperature, the faster the time it takes to decompose the same quality wood.

4.2.2 The influence of pH and moisture level

Rengel Z. et al. found that climatic factors may affect the pH of the soil. Increases in temperature or rainfall will increase the biomass in the ecosystem, which in turn will increase

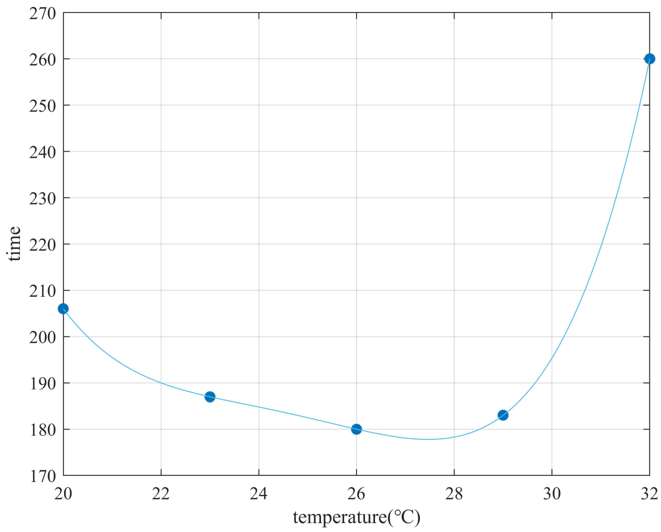


Figure 7: Time for complete decomposition of wood at different temperatures

the degree of soil acidification. At the same time, due to the increase in rainfall, cations in the soil may be transferred to surface water and groundwater, leaving acidic soil.[6]

According to Figure 8, we found that alkaline soils are mainly distributed in the Middle East, including the eastern and southern parts of the Mediterranean. The climate here is characterized by tropical desert climate, Mediterranean climate and temperate continental climate. The biggest feature of this area is drought, which is consistent with the conclusion we got before: the land in the arid area shows alkaline.

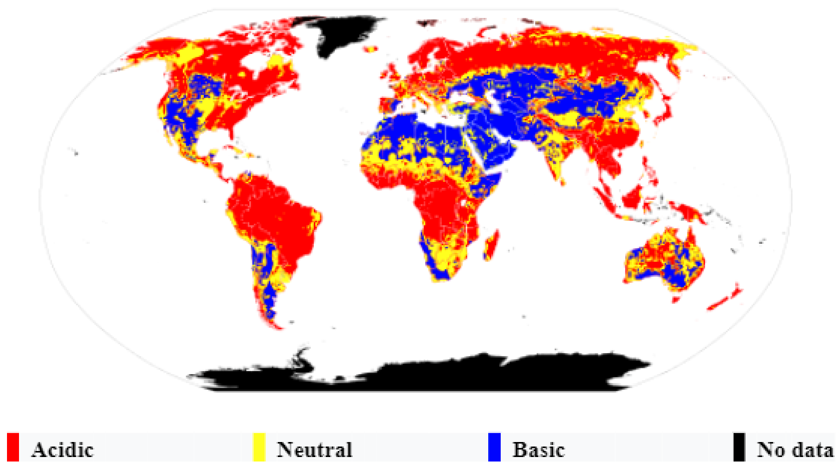


Figure 8: The world map of pH [7]

Therefore, it can be assumed that the acidity of the soil gradually rises from arid regions to tropical rain forests.

Regarding the moisture level, the moisture content of the tropical rain forest gradually rises from drought. Regarding temperature, it is difficult to measure the temperature between arid regions and tropical rainforest regions, so we need to separately consider the impact of temperature on the advantages and disadvantages of species.

According to relevant research data, the soil pH of the Amazon tropical rain forest is between

4.17-4.94 [8], and the soil pH in arid areas is between 7.5-8.0 [9].

Assuming that the pH value and moisture level change uniformly in these five environments, calculate the ph and moisture level in the five environments respectively, and the obtained parameters are shown in Figure 9 and Table 5. Among them, I means arid area,II means semi-arid area, III means temperate area, IV means forest area,V means rain forest area.

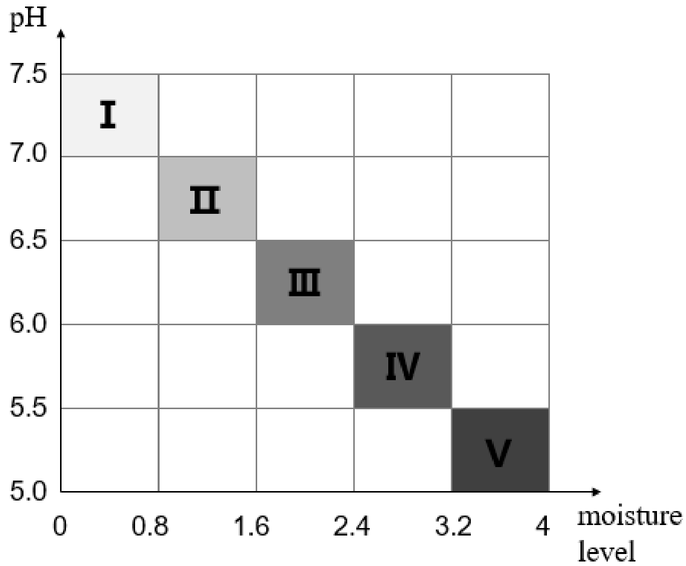


Figure 9: pH - moisture level matri

Table 5: The pH and moisture level of five environments

environment	pH	moisture level
arid	$7.0 - 7.5$	$0 - 0.8$
semi-arid	$6.5 - 7.0$	$0.8 - 1.6$
temperate	$6.0 - 6.5$	$1.6 - 2.4$
forest	$5.5 - 6.0$	$2.4 - 3.2$
rain forest	$5.0 - 5.5$	$3.2 - 4.0$

Two fungi Armillaria_gallica_HHB12551_C6C and Armillaria_tabescens_FP102622_A3C were selected for experiment.

Since the temperature of the five areas has no definite change rule, it may be assumed that the temperatures of the five areas are equal and equal to the average temperature of the two fungi at 26.65°C. The pH and moisture level of each area change within a certain range, and the midpoint of the change range is selected as the pH and moisture level of the area. Substituting all the above parameters into equation (8) (15), the result is shown in Figure 10.

It can be seen from Figure 10 that the number of No.1 fungi eventually stabilized at a non-zero value in any region, and No.2 fungi eventually died out. But changes in temperature and pH changed the decomposition rate and maximum number of the two bacteria. From arid area to tropical rain forest area, the change trend of the maximum number of the two kinds of fungi is firstly larger and then smaller.

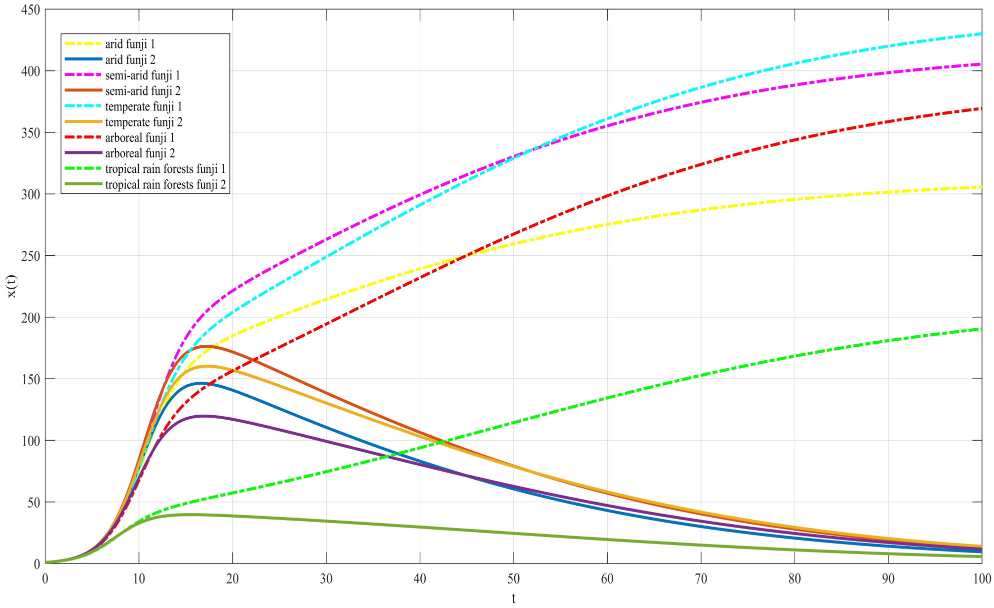


Figure 10: The quantitative relationship between two fungi in five regions

5 Model application: biodiversity's impact on decomposition efficiency

Biodiversity has always been a concern of researchers. Increasing biodiversity can improve ecosystem functions and accelerate the rate of ecosystem material circulation. This idea contained in "Origin of Species" has been confirmed by more and more scholars. This section uses a simplified mathematical model to explore the impact of the diversity of biofungal decomposers on the decomposition efficiency of wood materials.

This section first changes the number of biological species to explore changes in decomposition efficiency, and then explores the effect of species diversity on the decomposition process when environmental variables change.

5.1 The number of fungi's effect on the decomposition efficiency

As the types of fungi increase, a complex relationship network will be formed between them. In addition to the competitive relationship considered in the previous section, there may also be mutual assistance relationships between species. This complex relationship adds difficulty to the establishment of the model. In order to simplify the analysis, three types of fungi are used as the research objects, and the situation of extending to more fungi types is reasonably predicted.

According to the theory of ternary closure, only the following three relationships are stable for species under the ternary network: three species compete with each other, three species help each other, two species compete with each other, and the other one with the first two Mutual assistance (as shown in Figure 11).

When three species compete with each other, $G_i(t)$ is represented by the equation (16):

Figure 11: Schematic diagram of two species competing with each other and the other one helping each other with the first two species

$$G_i(t) = \frac{\mathrm{d}x_i(t)}{\mathrm{d}t} = \gamma_i x_i \left(1 - \frac{x_i}{N_i} - \sigma_{ij}\frac{x_j}{N_j}\right) \tag{16}$$

When three species help each other, $G_i(t)$ is represented by the equation (17):

$$G_i(t) = \frac{\mathrm{d}x_i(t)}{\mathrm{d}t} = \gamma_i x_i \left(1 - \frac{x_i}{N_i} + \sigma_{ij}\frac{x_j}{N_j}\right) \tag{17}$$

When the three species have both competition and mutual assistance, $G_i(t)$ is represented by the equation (18):

$$\begin{aligned} G_1(t) = \frac{\mathrm{d}x_1(t)}{\mathrm{d}t} &= \gamma_1 x_1 \left(1 - \frac{x_1}{N_1} - \sigma_{12}\frac{x_2}{N_2} + \sigma_{13}\frac{x_3}{N_3}\right) \\ G_2(t) = \frac{\mathrm{d}x_2(t)}{\mathrm{d}t} &= \gamma_2 x_2 \left(1 - \frac{x_2}{N_2} - \sigma_{21}\frac{x_1}{N_1} + \sigma_{23}\frac{x_3}{N_3}\right) \\ G_3(t) = \frac{\mathrm{d}x_3(t)}{\mathrm{d}t} &= \gamma_3 x_3 \left(-1 - \frac{x_3}{N_3} + \sigma_{32}\frac{x_2}{N_2} + \sigma_{13}\frac{x_1}{N_1}\right) \end{aligned} \tag{18}$$

In order to explore the influence of the diversity of fungal communities on the efficiency of lignocellulosic decomposition, we set different parameters to complete the simulation experiment several times. The experimental materials were Armillaria_gallica_SH1_A4A, Armillaria_sinapina_PR9 and Xylobolus_subpileatus_FP102567_A11A.

The parameters of the three fungi are shown in Table 6.

Make all environmental conditions in the most suitable conditions and remain unchanged, the time required for a single species to decompose wood is shown in Table 7, and the time required for multiple species to decompose the same wood is shown in Table 8.

According to the experimental results, in the case of multiple species, when multiple species are in a mutual assistance relationship, the time required to decompose wood materials of the same quality will be shorter. This is because a variety of fungi produce different types of

Table 6: The parameters of the three fungi

No.	fungus name	γ	moisture tolerance	ranking
1	Armillaria_gallica_SH1_A4A	0.76	0.177229	0.402694
2	Armillaria_sinapina_PR9	0.77	0.221719	0.367607
3	Xylobolus_subpileatus_FP102567_A11A	0.77	-0.5068	0.493197

Table 7: the time required for a single species to decompose wood

Fungus species	No.1 fungi	No.2 fungi	No.3 fungi
time	61	59	56

Table 8: the time required for multiple species to decompose wood

relation	competitive	cooperative	both
time	172	49	62

enzymes during the decomposition process, which synergistically decompose wood materials and intermediate products, thereby improving the decomposition efficiency. However, when the three fungi are in competition with each other, the three will compete with each other for nutrient resources, reducing the decomposition efficiency of their enzymes, making it take more time to decompose wood materials of the same quality. When competition and mutual assistance exist at the same time, the time required is between the above two situations.

Generally speaking, as the diversity of species increases, the relationship between species becomes more complicated, and the different relationships between organisms make the decomposition efficiency change greatly, that is, it may have a higher decomposition efficiency or a lower decomposition efficiency.

It can be seen from experiments that when the fungus in the ecosystem is more cooperative, it will make the decomposition efficiency higher and accelerate the carbon cycle. When the competition between fungi is strong, the decomposition efficiency will decrease instead.

5.2 The impact of environmental changes on biodiversity

To further explore the role of biodiversity in maintaining the stability of decomposition efficiency when the environment changes, three temperature conditions are specified: 15℃, 25℃, and 35℃. Design a new experiment to analyze the decomposition process under three temperature conditions, and calculate the volatility of the time required to completely decompose wood under different species conditions. Randomly select three fungi to conduct a series of experiments, and record the time required for a single strain and multiple strains to decompose wood of the same quality at different temperatures. Use the experimental data to draw Figure 12.

From Figure 12, we can see:

- At the same temperature, the distribution range of the decomposition time of wood when multiple fungi act together is larger than when one fungus acts alone. The possible reason

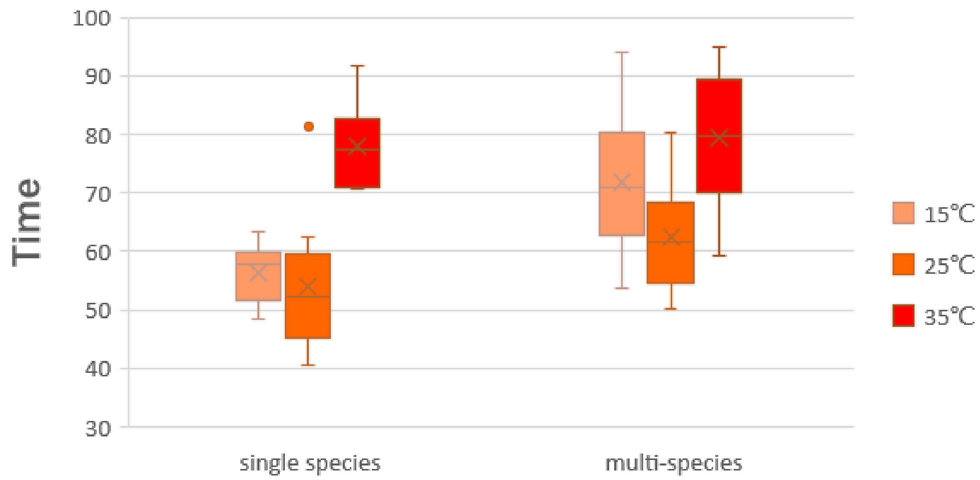


Figure 12: The time required for a single strain and multiple strains to decompose the wood at different temperatures

is that the diversity of species makes the interaction between species more complicated and the difference in decomposition efficiency is greater

- At the same temperature, the average decomposition time of multiple species is longer than that of a single species.
- When the temperature changes drastically, the variation range of the mean value of the decomposition time of multiple species is smaller than that of a single species; indicating that the diversity of species can improve the stability of the ecosystem during environmental fluctuations.

6 Sensitivity analysis

In the aforementioned model, the environmental capacity N, the initial number of fungi x_0 and other factors will affect the time it takes for fungi to decompose wood. Therefore, by changing the parameters, comparing the original results and the results after changing the parameters, the sensitivity of the two models in this article is analyzed.

In the model, the number of fungi in the initial state is given, but the number of different types of fungi varies greatly under natural conditions. In order to verify the stability of the model, we changed the initial value of the equation within the range of 10% and 20%, and observed whether the result would change drastically. By solving the equation of the system under the new initial value, observe the influence of the initial value change on the result, and the result obtained is shown in Table 9:

Table 9: the influence of the initial number of fungi change on the result

Initial number of fungi	-20%	-10%	0	10%	20%
Decomposition time	+1.95%	+0.97%	0	-0.97%	-1.46%

When the initial value of the number of fungi fluctuates by 10%, the decomposition time will fluctuate by 0.97%. When the initial value fluctuates by 20%, the decomposition time will fluctuate by 1.46% or 1.95%. It can be concluded that the decomposition time of wood materials is not sensitive to changes in the initial number of fungi, and the model is stable.

In the model, we assume that all fungi have the same environmental capacity N under optimal conditions. But in fact, the environmental capacity N of different kinds of fungi under optimal conditions is different. Therefore, it is necessary to consider the sensitivity of the model to the environmental capacity of the fungus under optimal conditions.

The results are shown in Table 10. The decomposition time of wood materials is not sensitive to changes in the value of the environmental holding capacity. When the environmental holding capacity N increases by 1%, the decomposition time decreases by 1.95%, and when the environmental holding capacity N decreases by 2%, the decomposition time increase by 6.82%. he above results indicate that the model is stable.

Table 10: the influence of environmental capacity change on the result

Environmental capacity	-2%	-1%	0	1%	2%
Decomposition time	+6.82%	+1.95%	0	-1.95%	-4.87%

7 Strengths and Weaknesses

7.1 Strengths

1. A negative exponential model is used to describe the change in wood quality, rather than a simple linear decline, which makes the model more realistic.

2. The data samples were obtained by Daniel S. Maynard and other scholars (through actual experiments .The data is accurate.

3. Through the global map of pH, the water level and pH are creatively linked, which simplifies the analysis process of the model without reducing the accuracy of the model.

4. This article starts with the analysis of the effect of a kind of bacteria, and then gradually increases the species of organisms to verify the role of biodiversity with a simplified model.

7.2 Weaknesses

1. When considering the influence of biological characteristics on the decomposition rate, we only considered moisture resistance and growth rate. In fact, there are many other factors that affect the decomposition rate of fungi, such as offensive ability and defensive ability.

2. For the multi-species competition model, we only calculated the competition between three species at most. With the increase of biodiversity, the competition relationship becomes more complicated, which is one of the improvement directions of the model.

3. The data used in this article contains only 37 fungi samples, the universality of the model needs to be improved.

References

[1] Nicky Lustenhouwer, Daniel S. Maynard, Mark A. Bradford, Daniel L. Lindner, Brad Oberle, Amy E. Zanne, and Thomas W. Crowther, "A trait-based understanding of wood decomposition by fungi," Proceedings of the National Academy of Sciences of the United States, May 13, 2020. https://www.pnas.org/content/pnas/117/21/11551.full.pdf

[2] https://stock.tuchong.com/image?imageId=985966015613239317

[3] Daniel S. Maynard. Consistent trade-offs in fungal trait expression across broad spatial scales. *nature microbiology*.

[4] Olso n, J.S.Energy storage and balance o f producers and decomposers in ecological systems[J] .*Ecology*, 1963, 44(2) :322-331.

[5] https://zh.wikipedia.org/wiki/%E6%9C%A8%E8%85%90%E7%9C%9F%E8%8F%8C

[6] Rengel Z. (2011) Soil pH, Soil Health and Climate Change. In: Singh B., Cowie A., Chan K. (eds) Soil Health and Climate Change. Soil Biology, vol 29. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-20256-8_4

[7] https://zh.wikipedia.org/wiki/%E5%9C%9F%E5%A3%A4pH%E5%80%BC

[8] Negreiros, G. H. de; Nepstad, D. C. 1994, Mapping deeply rooting forests of Brazilian Amazonia with GIS, Proceedings of ISPRS Commission VII Symposium - Resource and Environmental Monitoring, Rio de Janeiro. 7(a):334-338.

[9] http://celosangeles.ucanr.edu/Agriculture/High_Desert_Soils/

Appendices

Don't Overlook the Ecological Roles of Fungi

As known to all, fungi seems to be everywhere in our lives, mushrooms on the roadside, moss on the bark or yeast in food, etc., but there is more to fungi than just mushrooms or moss. They are the most effective organic decomposer on the earth. At present, humans have discovered nearly 120,000 kinds of fungi, and they have different forms, from 10uM single-celled fungi to macroscopic mushrooms. As a member of the global ecosystem, they play an important role in it.

Firstly, participate in the carbon cycle and nutrient cycle, affecting greenhouse gas emissions and fixation. Fungi play an important role in carbon cycle and nutrient cycle. They are the main decomposers of wood and garbage. They decompose the carbon-containing macromolecular organic matter obtained by animals and plants from nature, so that the carbon can be used in other forms, thereby achieving the effect of promoting the carbon cycle. At the same time, fungi in the soil can also participate in the nutrient cycle in the ecosystem and assist the transfer of nutrients in the soil to plants. Taking mycorrhizal fungi as an example, they can accumulate nitrogen (N) and phosphorus (P) in the natural environment, and Provided to the host plant.

Secondly, decompose plant litter and promote the formation of humus. The decomposition of the litter layer contributes to the formation of soil humus and provides nutrients to a large number of microorganisms in the soil. Fungi use their own extracellular enzymes to decompose lignocellulose, which is difficult for other organisms to decompose. Studies have shown that fungi first decompose easily decomposable substances in litter, such as cellulose, hemicellulose or organic acids, and then decompose more difficult substances, such as lignin or cork. Therefore, researchers generally use a negative exponential model to study the quality decomposition in the decomposition process of the litter layer.

Combined with the previous research on the decomposition efficiency of fungi, scientists have found that the rate at which fungi decompose wood is closely related to some characteristics of fungi. Among them, mycelial elongation has a clear positive correlation with fungi's moisture resistance.

Thirdly, interact with other organisms to maintain the stability of the ecosystem. On the one hand, for plant communities, studies have shown that host plants that coexist with mycorrhizal fungi can interact through the mycelial network, allowing subdominant species to survive in the presence of events. Approximately 90% of all plant species have mycorrhizal chaperones. In the process of mutual benefit between fungi and plants, species diversity in some ecosystems increases and ecosystem stability increases. On the other hand, for the soil biological community, fungi decompose the humus of animals and plants, which also creates a good living environment for soil microorganisms.

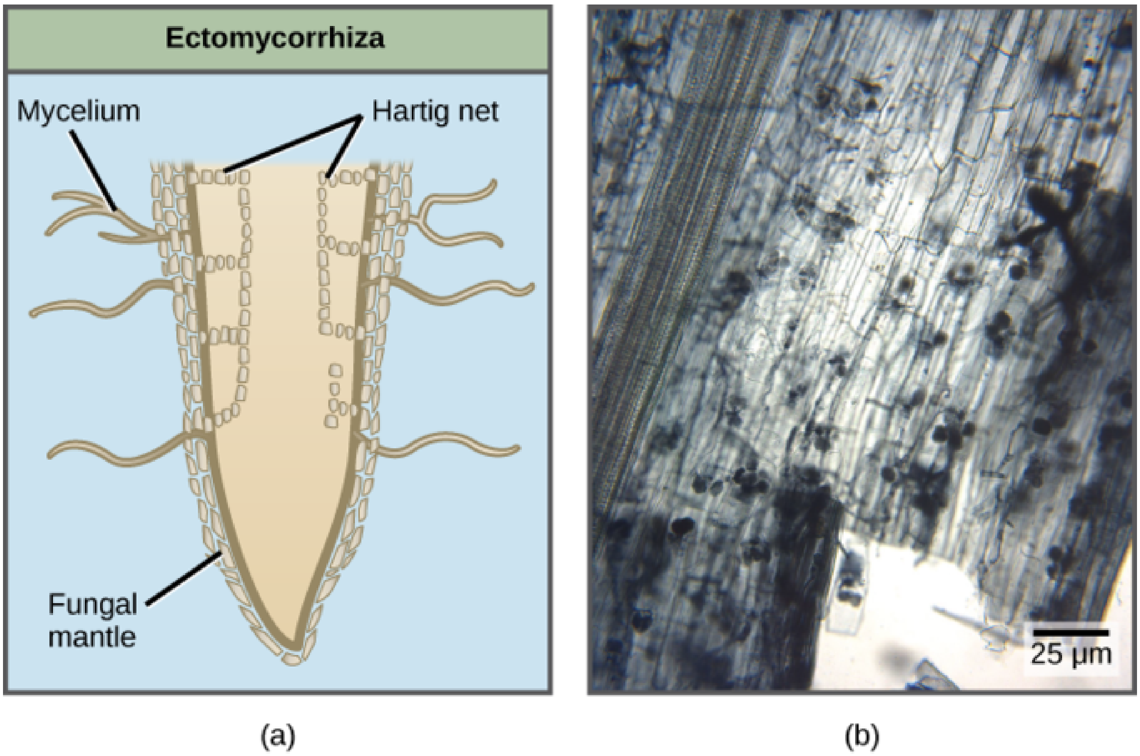


Figure 13: Mycorrhizal fungi: (a) Ectomycorrhiza and (b) arbuscular mycorrhiza have different mechanisms for interacting with the roots of plants.

At the same time, our research shows that in the drastic changes of the environment, the increase of fungal diversity is also conducive to the stability of the ecosystem. Taking the decomposition of wood material as an example, through numerical analysis, when the ambient temperature is increased by 10℃, the decomposition time of a single fungus increases by 44% on average, but only by less than 23% in the case of multiple species. This provides strong proof for the idea that fungal diversity can improve the ecosystem's resistance to changes in the external environment.

In general, fungi play an important role in maintaining the stability of ecosystem diversity. It is meaningful to study them systematically and analyze their interactions with other organisms.