Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
A		2118521

Fungi's Contribution to Carbon Cycle through Competition Model

Carbon cycle is crucial to climate change and human living environment. Fungi are the key agents to decompose woody fibers. In this paper, a kinetic model of wood decomposition is proposed where the interactions between different fungi types are taken into consideration. The model is used to analyze the difference of decomposition benefits, relative advantages and disadvantages of fungal combinations under different temperatures and humidity.

Regression models are constructed to describe the relations between temperature and fungal growth rate, moisture and fungal moisture tolerance. This model aims to measure the fungal decomposition of the ground litter and woody fibers due to the presence of multiple species of fungi. The kinetic equations of fungal growth rate, moisture tolerance and decomposition rate are proposed.

To measure the interactions between the different fungi types, we use the Logistic population model to establish an interspecific competition model for any two given fungi. We can obtain the relative competitiveness between two fungi by using the fungi's density increasing rate to represent its growth rate and the ratio of decomposition rate to measure the fungi's competition coefficient.

Based on the interspecific competition model, we draw trend charts of fungal competition through simulation. We find that rapid temperature and humidity changes have different effects on the interspecific competition. Fungi are more sensitive to temperature than moisture. When the temperature changes sharply, the competitiveness of the fungi changes.

To further measure each fungus' competitiveness to temperature, we use the ratio matrix to calculate the marginal competitiveness of each fungus under different temperatures. Considering the simulation of long- and short-term temperature changes in fungi's competitions, we find that the larger the standard deviation of fungi's marginal competitiveness is, the more sensitive fungi are to temperature changes. The dominant fungi species vary as temperature changes. Besides, the marginal competitiveness of fungi under different humidity conditions depends on their moisture tolerance coefficients. The higher the coefficient is, the lower the competitiveness is. In this case, such fungus is relative disadvantaged.

To find suitable combinations of fungi in different climates, we look for combinations that are likely to persist based on competitive rankings of temperatures and humidity. We find combination 1 (*Phlebia acerina MR4280 B9G* and *Phlebia acerina DR60 A8A*), and combination 2 (*Armillaria sinapina PR9* and *Phellinus robiniae AZ15 A10H Banik/Mark*) which are both symbiosis pairs. Moreover, through the long- and short-term temperature and humidity change analysis, it is confirmed that these two combinations have an apparent competitive symbiosis.

The experimental results show that the above two fungal combinations have no advantage in the competition with fungi which have strong marginal competitiveness under specific environmental conditions, but they have significant advantages in the long-term fluctuation of the natural environment. The adaptive ranges of temperature and moisture of these two fungal combinations are much broader than any component fungus of these combinations.

Keywords: decomposition, logistic model, competition model, marginal competitiveness

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1. Introduction

1.1 Background

The carbon cycle includes a crucial carbon exchange process between the biosphere and the atmosphere. One vital portion of this cycle is the decomposition of compounds which allows the carbon to exist in other forms inside the cycle. Fungus, as an important decomposer, participates in the process by decomposing animal debris as well as plants debris like woody fibers.

Fungal decomposition is a complex process and highly determined by fungal traits including physiological growth traits like hyphal extension rate, ecological performance traits like optimal moisture and biochemical traits in the individual level (Maynard et al., 2019). However, among these factors, Lustenhouwer et al. (2020) point out that hyphal extension rate (growth rate of fungus) and moisture trade-off (fungus's moisture tolerance) have a major impact on fungus' decomposition rate.

Further, when multiple species of fungi exist in the same decomposition process, there would be a competition for space among them (Maynard et al., 2017). It is still uncertain that how the diversity of fungus would impact the decomposition rate of woody fibers and to what extent the diversity would enhance the ability of a fungal community to resist extrinsic environmental variations.

1.2 Restatement of the Problem

We are required to examine the role of fungal community in the decomposition process of ground litter and woody fibers in a fixed pitch of land. When evaluating the decomposition rate of different fungi, we take two of their traits into account: growth rate and moisture tolerance. Further, the question will be analyzed into five parts:

1. Build a model to describe the decomposition rate of multiple fungi in a given temperature and moisture environment without considering the interactive affects among different fungi.
2. Take the interactions between fungi into account to further modify the model.
3. Describe the interaction dynamics between different fungi in both short- and long-term by analyzing the sensitivity of a fungal community to rapid fluctuations in the environment as well as to overall influence of slowly changing atmospheric conditions.
4. Figure out the relative advantages and disadvantages of each individual fungus and fungi combinations which are possibly to survive. Moreover, analyze these properties in other environments such as arid, semi-arid, temperate, arboreal and tropical rain forests.
5. Show to what extent the diversity of a fungal community system affects the efficiency of a ground litter decomposition system. Predict the cruciality and role of biodiversity given various degrees of diversities in the local environment.

1.3 Overall analysis of the problem

To construct a mathematical model of the fungi activities, we can try to build up the connection based on the growth and moisture tolerance. Based on the paper given, the growth rate is highly related to the temperature and the moisture tolerance is highly related to the environmental humidity.

In order to interpret the interactions between different fungi types, we need to build a kinetic model to estimate the competitions between each two fungi.

To evaluate the sensitivity of fungi in short- and long-term trends of the environmental changes, we can use the computer simulation to implement the kinetic model that we have built.

To evaluate the relative advantages and disadvantages of each species, we weigh the marginal effect for each fungus species. For the combinations of species, the intersection of the marginal effect in different environments can be used to evaluate the sensitivity for each fungal combination.

2. Assumptions and Justifications

In order to simplify our model, we give a couple of assumptions and each of them is justified properly:

1. **In a given material area for fungus growth, there is a maximum colony density which does not change with time.**

Reason: Since the growth of fungus is restricted by extrinsic conditions like space and organic compound, fungus cannot proliferate without bound in a unit culture material, i.e., there is always a maximum density bound for fungus growth.

2. **There is only competitive relationship between two fungi species.**

Reason: Based on the research from Shearer (1995), the author shows compelling evidence about the occurrence of fungal competition in nature.

3. **Competition among three fungi species is not considered.**

Reason: We do not consider the case that two fungi species unite to compete with another species. We consider the competition between each pair of these three.

4. **Whatever the climate zone it is, the climate changes periodically throughout a year.**

Reason: All climate zones have its climate varied to different extents for the four seasons in a year.

3. Notation

Abbreviation	Description
T	Temperature (°C)
θ	Moisture (MPa)
$\alpha_i (i = 1, 2, \cdots, 34)$	i^{th} moisture tolerance coefficient
k_w	Empirical coefficient of moisture tolerance
n_w	Exponential coefficient of moisture tolerance
f	Extension/growth rate of fungus
g	Moisture tolerance
D	Decomposition rate
k	Maximum fungal density
$x_i (i = 1, 2, \cdots, 34)$	i^{th} fungal density
$s_{m.n}$	Competitive coefficient between m^{th} and n^{th} fungus
c_i	Relative marginal competitiveness of temperature

4. Decomposition rate model based on temperature and moisture tolerance

4.1 The relationship between temperature and fungus growth rate

We plot the logarithm of growth rate logarithm of each fungi species with respect to temperature in Figure 1. It is not hard to see that there is a positive correlation between decomposition and temperature. Besides, the logarithm has a linear trend with respect to temperature (The color that each fungus represents is in Appendix A).

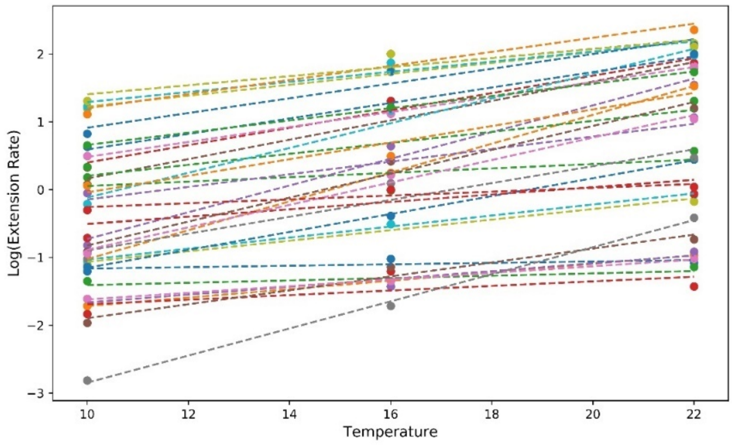

Figure 1 The correlation between temperature and growth rate of 34 fungi species

By this linear trend, we deduce the relationship between temperature and growth rate in an exponential form:

$$f(T) = e^{b-aT}$$

where a and b are growth rate coefficients.

4.2 The relationship between moisture and moisture tolerance

According to a review literature regarding fungus decomposition rate with respect to the effect of moisture (Walse et all., 1998), the relationship between moisture and moisture tolerance can be expressed by Langmuir adsorption isotherm for physical adsorption of water to a particulate solid. They apply relative soil moisture saturation (the ratio between soil moisture content and maximum water-holding capacity) to define the moisture condition for fungus. The reason this holds true is that soil moisture saturation describes the water proportion in soil, which is crucial for fungus to exert decomposition and material exchange. Thus, we can use Langmuir adsorption isotherm formula to evaluate the moisture condition for different fungi with a few modifications as shown below:

$$g(\theta) = \frac{k_w(\alpha_i\theta)^{n_w}}{1 + k_w(\alpha_i\theta)^{n_w}}$$

where k_w and n_w are empirical coefficients. In our condition, these two values are obtained from fungus's cellulose decomposition experiment conducted by Rosswall and Berg (1972). Their experiment done on cellulose is applicable in our model as woody fibers and ground litter are chemically similar. Additionally, to characterize fungi's different adaptabilities to moisture conditions, we can figure out a moisture tolerance coefficient α_i for each fungi species from the correlation coefficient between decomposition rate and moisture tolerance.

4.3 The decomposition rate model

For each fungi species, growth rate and moisture tolerance work together on decomposition rate rather than influence each other. Thus, we consider the correlation of the product of growth rate and moisture tolerance with the decomposition rate. Then we can calculate each species' moisture tolerance from the linear regression between growth rate and decomposition rate.

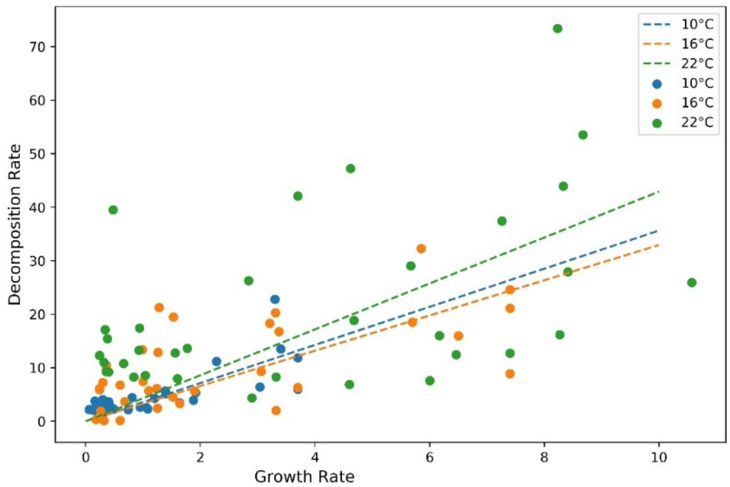

Figure 2 The correlation between growth rate and the decomposition rate of 34 fungi species in the temperature 10℃, 16℃ and 22℃

From Figure 2, in these three temperature conditions, the product has a positive correlation with the decomposition rate. Hence, we obtain the formula below:

$$D\left(T,\alpha_i,\theta\right)=f(T)g(\alpha_i,\theta)$$

$$=e^{b-aT}\frac{k_w(\alpha_i\theta)^{n_w}}{1+k_w(\alpha_i\theta)^{n_w}}$$

In terms of multiple fungi species, the total decomposition rate would be the sum of each species decomposition rate as we do not consider the interactions between fungi species at this stage.

5. Competition model between two different fungi

From the basic logistic model which describes the population size variations in a fixed environment, we have

$$\frac{dx_m}{dt} = f_{x_m}(T) \cdot x_m \cdot \left(1 - \frac{x_m}{k}\right)$$

$$\frac{dx_n}{dt} = f_{x_n}(T) \cdot x_n \cdot \left(1 - \frac{x_n}{k}\right)$$

given fungi species x_m and x_n.

Based on that, we construct the competition model between two fungi species

$$\frac{dx_m}{dt} = f_{x_m}(T) \cdot x_m \cdot \left(1 - \frac{x_m}{k} - s_{m,n}\frac{x_n}{k}\right)$$

$$\frac{dx_n}{dt} = f_{x_n}(T) \cdot x_n \cdot \left(1 - \frac{x_n}{k} - s_{n,m}\frac{x_m}{k}\right)$$

$$s_{m,n} = \frac{D_n}{D_m} \quad s_{n,m} = \frac{D_m}{D_n}$$

where $s_{m,n}$ is the ratio of decomposition rate between fungi species x_n and x_m.

Given the same initial population size, we take two fungi species as a sample to show the population size variations with respect to time based on our interaction model as shown in Figure 3.

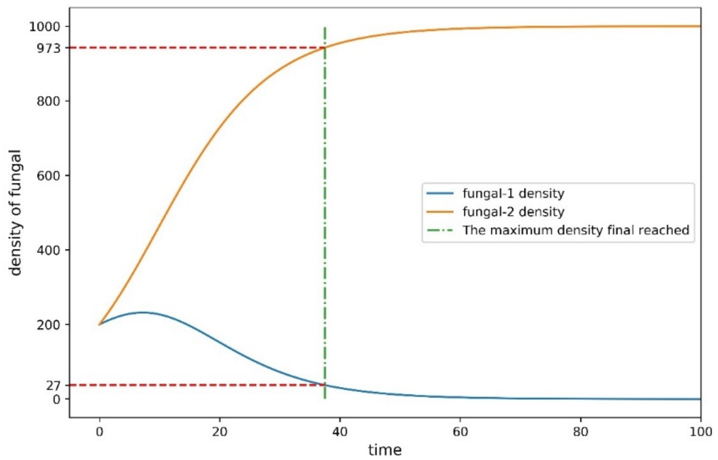

Figure 3 The population variations of two species with respect to time in a given temperature environment

When the sum of these two species' population sizes reaches the maximum density of a given space (1000 in this sample), we get the population size ratio of these two species. For the given 34 species, there are 561 different competitive combinations for two by two interactions. For each of 10℃, 16℃ and 22℃ temperature environments, we generate a matrix to show all 561 ratios between two competitive fungi species when the given space is fully occupied (see Figure 4 - 6).

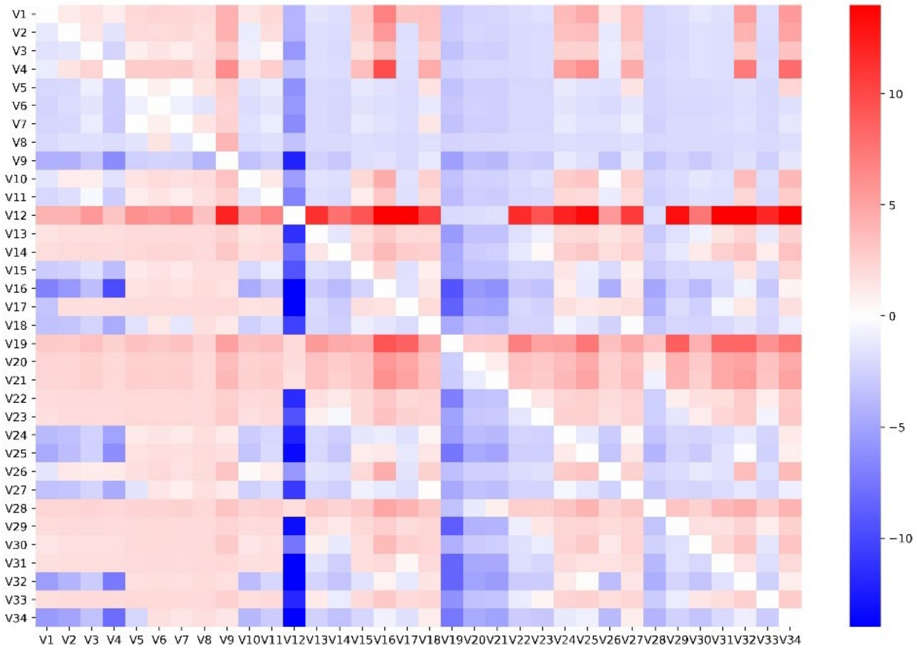

Figure 4 The ratios of two fungi species density at the maximum stage in a 10℃ temperature environment

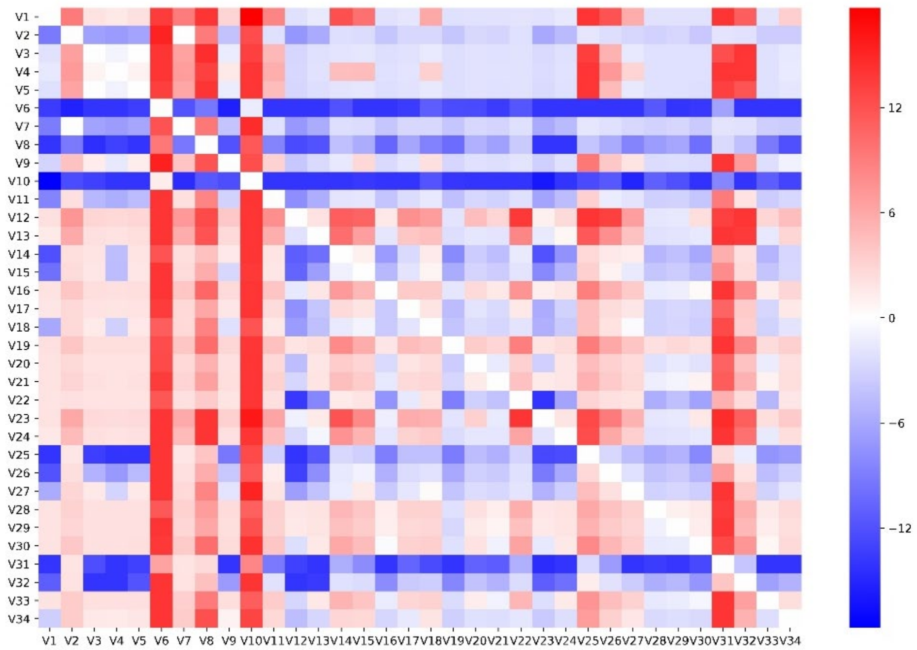

Figure 5 The ratios of two fungi species density at the maximum stage in a 16℃ temperature environment

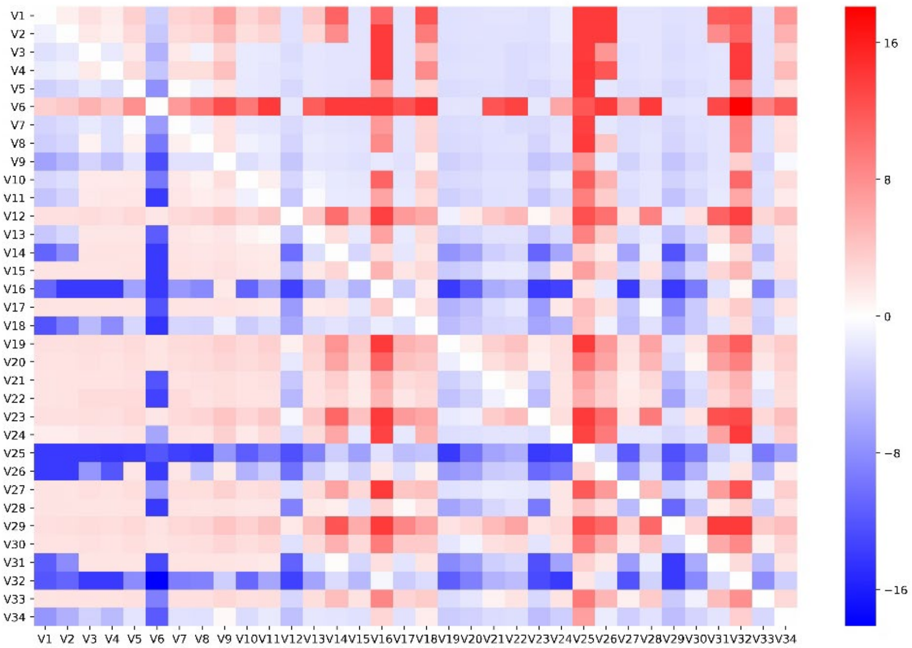

Figure 6 The ratios of two fungi species density at the maximum stage in a 22℃ temperature environment

In each of these matrices, one of its entries represents the logarithm (based on ten) of their ratios. Thus, the diagonal equals zero as the ratio of one fungi species population size itself is one. Besides, entries of the matrix are symmetric along the diagonal since the ratios of two species density are reciprocals with each other along the diagonal of the matrix and thus the logarithms of symmetric positions are strains.

The matrices indicate the relative competence between two fungi species given the same initial population density in a fixed environment. As we assume there is only competitive relation between any of two fungi species, these matrices describe the interactions between different types of fungi species.

6. Competition model simulation for the rapid fluctuations and long-term changing atmospheric variations in the environment

In this section, we would like to describe the dynamics of the competition model between any two fungi species when the given environment changes. We only consider two parameters variations in a changing environment—temperature and humidity. Besides, temperature and humidity changes could be rapid and slow in nature. For example, rainstorm in summer would decrease the temperature and increase the humidity sharply. In contrast, throughout a year, temperature and humidity have a periodic variation process in general. Thus, we analyze the dynamics of our competition model in both rapid fluctuations and long-term changing.

6.1 Competition model simulation for the rapid fluctuations

In the rapid fluctuations case, we analyze the sharp changes of temperature and humidity separately.

For ambient temperature, we increase or decrease it by 8℃ at 16℃ before the population density reaches the stability. Figure 7 below shows a typical population density variation sample between fungi species *Armillaria gallica FP102531 C6D* (V1) and *Armillaria gallica SH1 A4A* (V8).

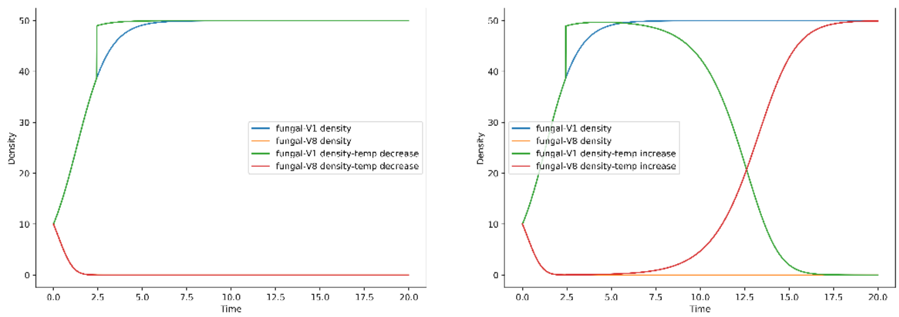

Figure 7 The population density changes of fungi species V1 and V8 when the ambient temperature (16℃) has ±8℃ variation in a short run

Figure 7 indicates two general cases when temperature changes. The left figure shows the accelerated population density variation case while the right one shows the population density cross case, i.e., the dominant species of this system changes when temperature changes. The accelerated case implies the similar short-term temperature change sensitivity between two species. In this sample, this shows that fungus V1 and fungus V8 are relatively equally sensitive to short-term temperature decrease. The cross case implies that one fungi species is more sensitive to short-term temperature change than the other one. Thus, fungus V1 is more sensitive to short-term temperature increase compared with fungus V8.

Besides, Figure 8 gives another case: competitive symbiosis between *Phlebia acerina MR4280 B9G* (V28) and *Phlebia acerina DR60 A8A* (V29) as temperature varies. The competitive symbiosis case implies that two fungi species are relatively equally sensitive to short-term temperature change. Thus, fungi species V28 and V29 are relatively equally sensitive to short-term temperature change here.

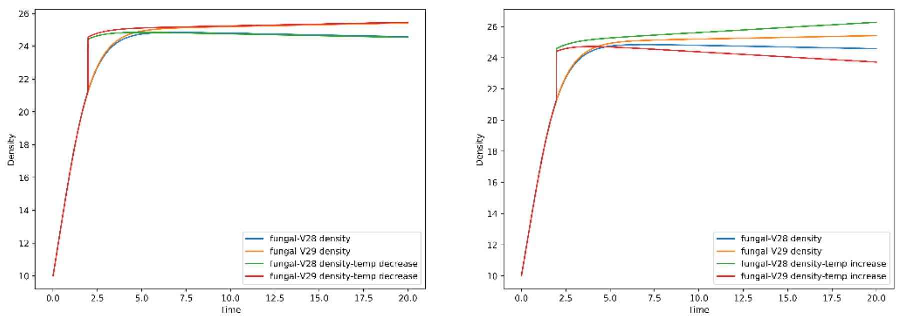

Figure 8 The population density changes of fungi species V28 and V29 when the ambient temperature (16℃) has a ±8℃ variation in a short run

Similarly, for moisture, we increase or decrease its value by 0.3MPa at -0.6MPa before the population density reaches the stability. Figure 9 shows a typical population density variation case between fungi species *Armillaria gallica EL8 A6F* (V2) and *Armillaria sinapina PR9* (V9).

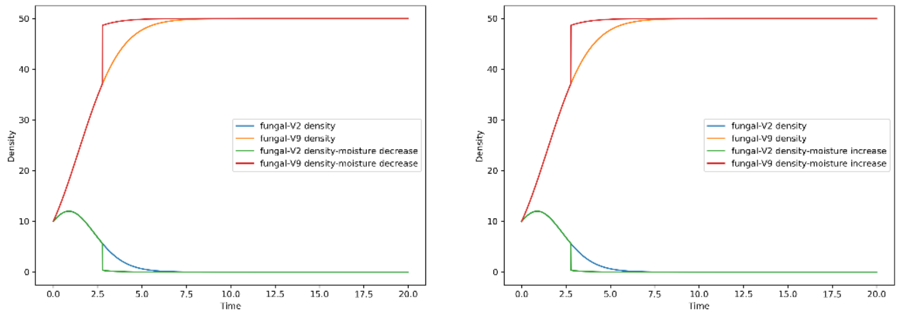

Figure 9 The population density changes of fungi species V2 and V9 when the moisture (-0.6MPa) has a ±0.3MPa variation in a short run

This is the accelerated population density variation case for moisture which is analogous to the accelerated version in temperature changes. The accelerated case implies the relatively equal short-term moisture sensitivity between two species. In this sample, fungi species V2 and V9 are relatively equally sensitive to short-term moisture change in the environment.

Also, we have the population symbiosis case between V28 and V29 when moisture changes as shown in Figure 10. Similarly, the symbiosis case implies that two fungi species are relatively equally sensitive to short-term moisture change. Thus, fungi species V28 and V29 are relatively equally sensitive to short-term moisture change here.

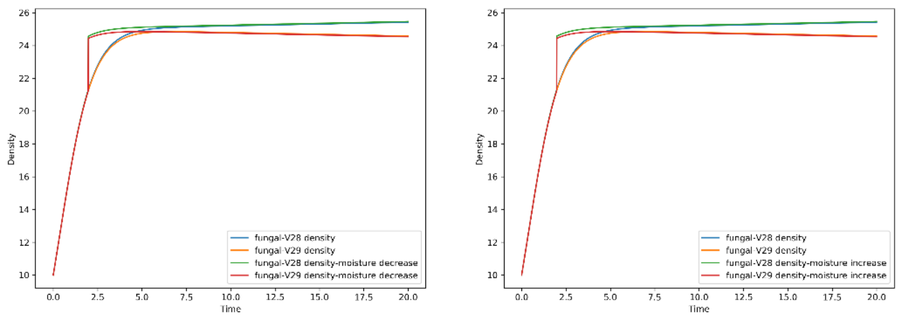

Figure 10 The population density changes of fungi species V28 and V29 when the moisture (-0.6MPa) has a ±0.3MPa variation in a short run

Note that when moisture varies, we do not have the dominance-exchanging case. Additionally, the impact of moisture changes on population size variation is relatively weaker. The reason is that moisture changes only result in small changes on the moisture tolerance $g(\theta)$.

6.2 Competition model simulation for the long-term changing atmospheric variations

In the rapid fluctuations case, we analyze the periodic changes of temperature and humidity separately. We apply the sine functions to simulate the periodic changes for these two parameters. To be more specific, temperature and moisture in four seasons in a year are simulated by four equally divided intervals within a period.

For temperature, we set the initial temperature as 16℃ and its maximum variation within a time period is 8℃. Based on that, we generate two figures in Figure 11 to describe the fungi population density variations within a temperature change period (left side) and throughout several periods (right side).

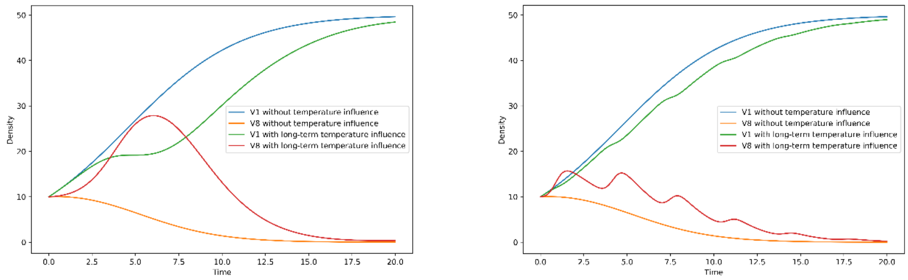

Figure 11 The population density changes of fungi species V1 and V8 when the temperature (16℃) has a ±8℃ variation within a period and throughout several periods

According to these two figures, the population density changes of these two fungi species have the same trend regardless of the number of periods. Thus, in the long run, periodic changing temperature pattern does not affect the population density variation trends of these two fungi species.

Similarly, we set the initial moisture as -0.6MPa and its maximum variation within a time period is 0.3MPa. Then we produce two figures in Figure 12 to represent the fungi population density variations within a moisture change period (left side) and throughout several periods (right side).

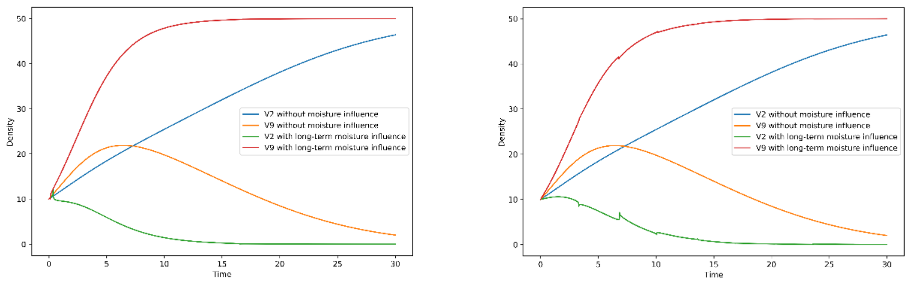

Figure 12 The population density changes of fungi species V2 and V9 when the temperature (-0.6MPa) has a ±0.3MPa variation within a period and throughout several periods

It is not hard to see that the high frequency of the variation does not affect the trend. Similarly, the population density variation trends of these two fungi species are nearly not influenced by moisture long-term changing pattern.

7. The analysis of environmental adaptability for different fungi species

7.1 Predictions about the relative advantages and disadvantages for each species

7.1.1 Relative marginal competitiveness of temperature (RMCT) for different fungi species

In order to measure the relative marginal competitiveness of temperature for each fungus, we apply the following formula to the ratio matrix of 34 fungi species at 10 ℃ (Figure 4) to obtain the relative marginal competitiveness c_i of the i^{th} fungus ($i = 1, 2, \cdots, 34$) species among n fungi species at 10 ℃ (n is 34 in this context):

$$c_i = \sqrt[n]{\prod_{i=1}^{n} x_i}$$

where x_i is the scaled area ratio of the i^{th} and j^{th} ($j = 1, 2, \cdots, n$) (when the one-to-one competition of these two species reaches the upper density limit.

In the same way, we can obtain the i^{th} ($i = 1, 2, \cdots, n$) fungi species' relative marginal competitiveness c_i among n fungi species in the two ratio matrices of 16 ℃ and 22 ℃ (Figure 5 and 6), respectively.

Then the fungi are sorted according to the relative marginal competitiveness of temperature for fungi at 10 ℃, 16 ℃ and 22 ℃. We take the average value of ranking as the horizontal axis data and take the name of each fungus as the vertical axis data to obtain the following box plot:

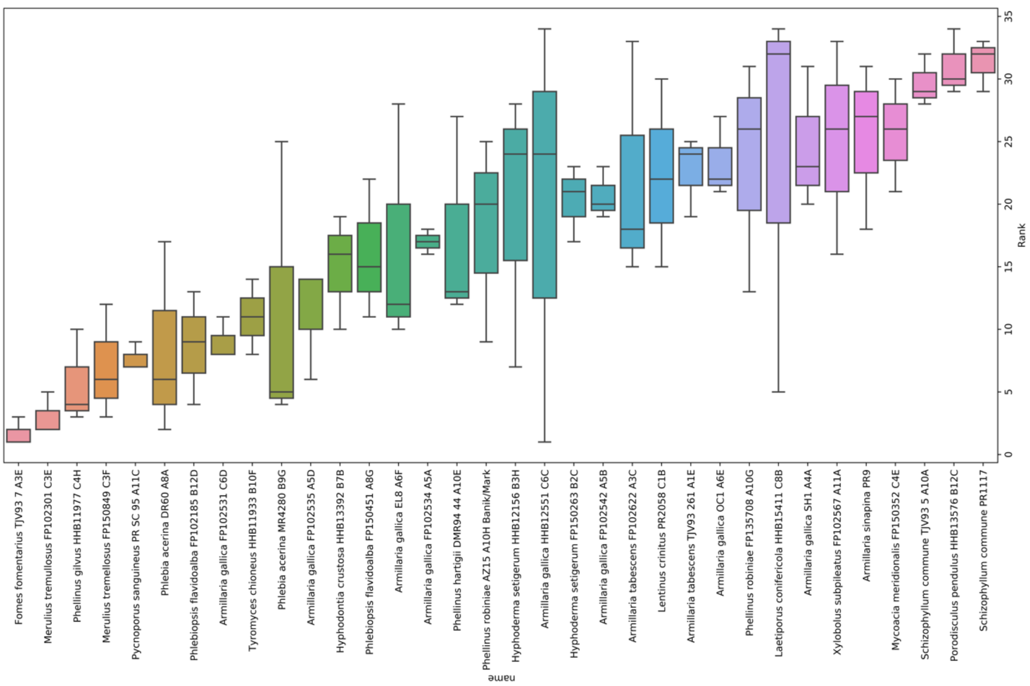

Figure 13 The ranking of relative marginal competitiveness of temperature for each fungus

From the horizontal axis, the relative marginal competitiveness of temperature increases from left to right. The sensitivity to temperature change can be inferred from the range size of each box, that is, if the range is small, the relative marginal competitiveness ranking of the fungus at different temperatures is relatively stable, and thus the sensitivity to temperature change is low; if the range is large, the relative marginal competitiveness ranking of the fungus at different temperatures changes greatly, and the sensitivity to temperature change is relatively high.

It can be concluded from Figure 13 that the left-side fungus box plot between any of the two fungi comparison represents the weaker relative marginal competitiveness of temperature, and such species are relatively inferior in the competition; while the right-side fungus box plot implies the stronger relative marginal competitiveness of temperature, and such species are relatively superior in the competition.

7.1.2 Absolute marginal competitiveness of moisture (AMCM) for different fungi species

By taking the moisture tolerance coefficient α as the independent value and moisture tolerance g as the dependent value, we generate Figure 14 shown below

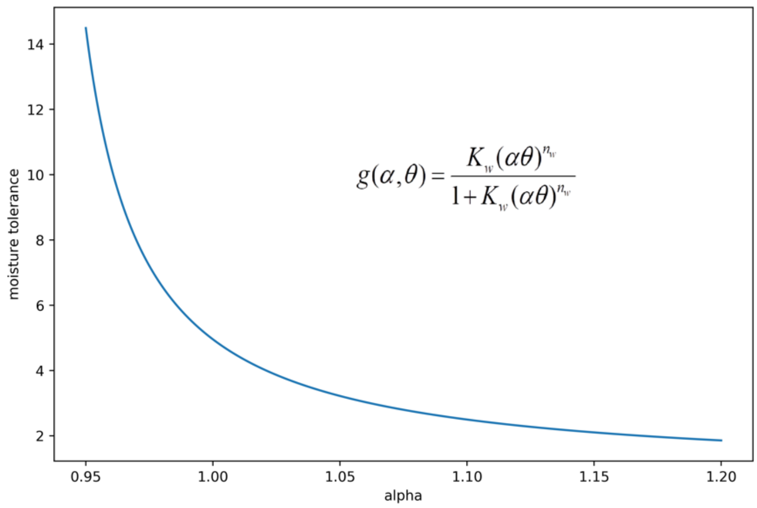

Figure 14 The change of moisture tolerance g with respect to moisture tolerance coefficient α

It can be seen from Figure 14 that the larger the temperature tolerance coefficient α is, the smaller the humidity tolerance is. In other words, the larger the temperature tolerance coefficient α is, the weaker the absolute marginal competitiveness of humidity is.

By the conclusion above, the absolute marginal competitiveness of fungi humidity can be ranked by α as follows:

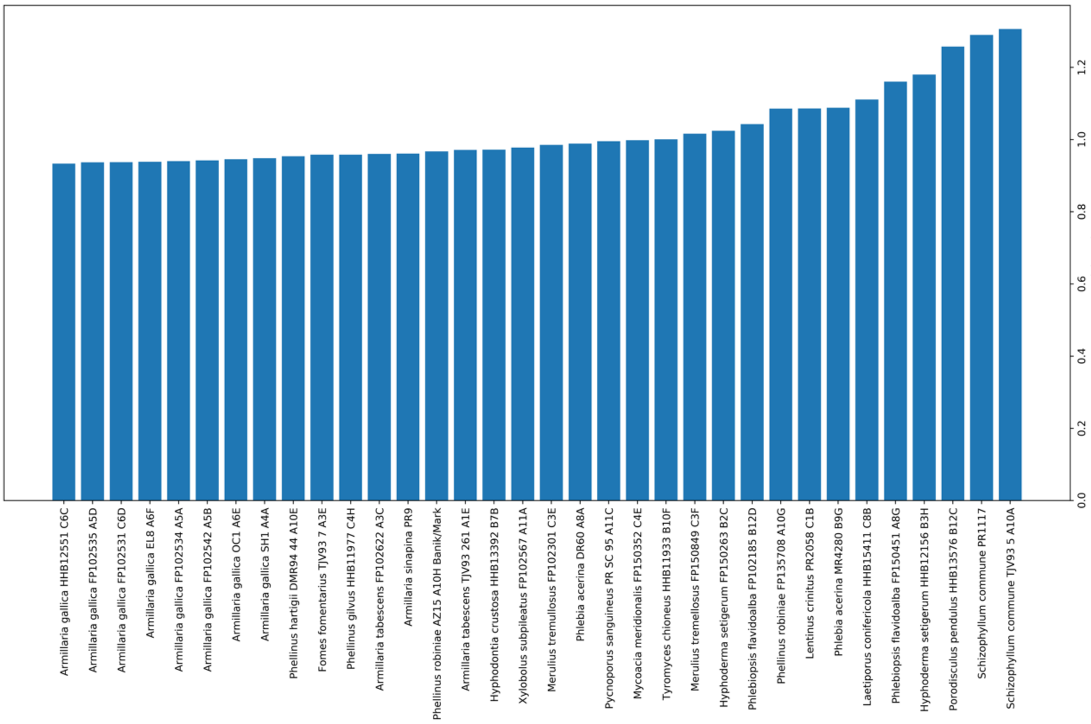

Figure 15 The ranking of absolute marginal competitiveness for different fungi species

It can be concluded from Figure 15 that the lower the rank is, the stronger the absolute marginal competitiveness of humidity is, and it has relative advantages in the competition with n species of fungi for humidity adaptation; the higher the rank is, the weaker the absolute marginal competitiveness of humidity is, and it has relative disadvantage in the competition with n species of fungi for humidity adaptation.

7.2 Predictions about the relative advantages and disadvantages for each combinations of species likely to persist

First, we need to give a set of combinations of fungi species that we suppose may exist for a long time. The principle is to minimize the competition intensity in these combinations so that component fungi can compete for a long time. Therefore, in our model, we believe that the fungi combination that may compete for a long time is the combination in which fungi species' ranks are close to each other.

According to Figure 15, the sensitivity of moisture for most fungi is similar. From Figure 14, it can be concluded that the sensitivity of temperature for fungi is quite different. Therefore, when judging the fungus combination that may exist for a long time, we decide to mainly use the relative marginal competitiveness rank of temperature to judge whether the competition rankings of fungi in the combination are close to each other. As for the absolute marginal competitiveness ranking of humidity, we take it as an auxiliary reference.

Finally, we find two competitive symbiotic fungi combinations: *Phlebia acerina MR4280 B9G* and *Phlebia acerina DR60 A8A* (Combination 1), *Armillaria sinapina PR9* and *Phellinus robiniae AZ15 A10H Banik/Mark* (Combination 2). The rank of temperature relative marginal competitiveness and moisture absolute marginal competitiveness of the two fungi combinations is shown as follows:

Table 1 The temperature relative marginal competitiveness ranking, average ranking and standard deviation of some fungi at the temperature of 10℃, 16℃, and 22 ℃

Combination	Name	10℃ RMCT	16℃ RMCT	22℃ RMCT	Average RMCT	10℃ Rank	16℃ Rank	22 ℃ Rank	Average Rank	α_i
1	Phlebia acerina MR4280 B9G (V28)	0.586	0.588	0.451	0.078	5	4	25	11.333	1.158
	Phlebia acerina DR60 A8A (V29)	0.483	0.583	0.640	0.079	17	6	2	8.333	0.996
2	Armillaria sinapina PR9 (V9)	0.382	0.519	0.426	0.070	31	18	27	25.333	0.983
	Phellinus robiniae AZ15 A10H Banik/Mark (V27)	0.419	0.502	0.554	0.068	25	20	17	20.667	0.962

- Combination 1

For combination 1, when applying the competition model developed in section 6 for prediction, it is found that with 16℃ as the initial temperature and -0.6MPa as the initial moisture, *Phlebia acerina MR4280 B9G* (V28) and *Phlebia acerina DR60 A8A* (V29) show a long-term symbiosis trend under the following conditions: (1) the short-term temperature changes dramatically (Figure 16); (2) the long-term temperature periodically fluctuates (Figure 17).

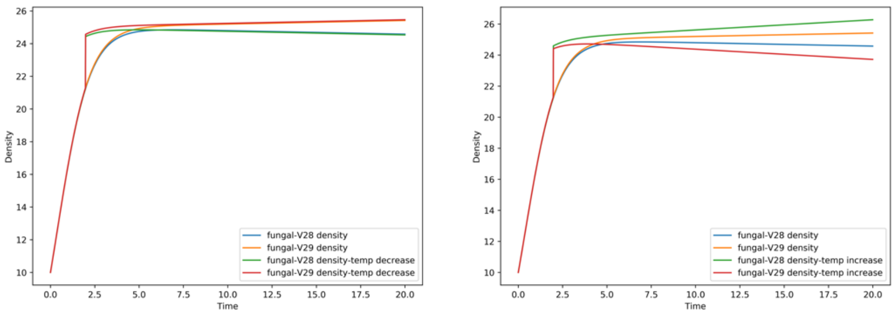

Figure 16 The competition graph of V28 and V29 in short-term drastic temperature change

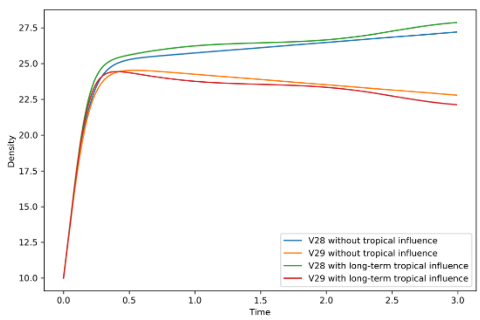

Figure 17 The competition between V28 and V29 in long-term temperature periodic fluctuation

- **Combination 2**

For combination 2, when applying the interaction model developed in section 6 for prediction, it is found that with 16℃ as the initial temperature and -0.6MPa as the initial moisture, *Armillaria sinapina PR9* (V9) and *Phellinus robiniae AZ15 A10H Banik/Mark* (V27) show a long-term symbiosis trend under the following conditions: (1) the short-term temperature changes dramatically (Figure 18); (2) the long-term temperature periodically fluctuates (Figure 19).

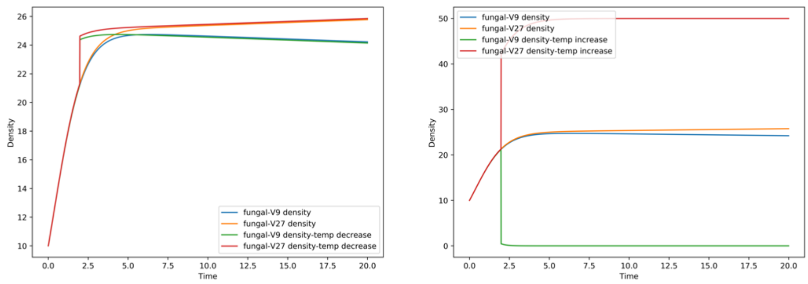

Figure 18 The competition between V9 and V27 in short-term drastic temperature change

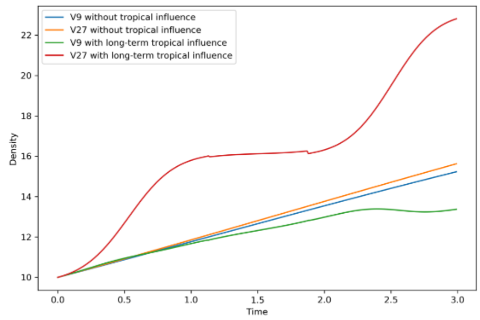

Figure 19 The competition between V9 and V27 in long-term temperature periodic fluctuation

- **The fungi combinations that are likely to persist**

According to Table 1, by comparing the temperature relative competitiveness rank and temperature tolerance coefficient of combination 1 and combination 2, we find that the relative advantages and relative disadvantages of the two fungi are different:

1. Combination 1 is stronger than combination 2 in the competition of temperature adaptation, because the average RMCT of combination 1 is significantly higher than that of combination 2. This gives rise to that the competitiveness of combination 2 is stronger than that of combination 1 in the environment of large temperature change. In other words, in the environment of large temperature change, combination 1 has relative advantage, while combination 2 has relative disadvantage.

2. Combination 1 is weaker than combination 2 in the competition of moisture adaptation, because the value of moisture tolerance coefficient of combination 1 is significantly higher than that of combination 2. This results in that the competitiveness of combination 2 is stronger than that of combination 1 in the environment with large moisture change, that is, in the environment with large moisture change, combination 1 has relative disadvantage, while combination 2 has relative advantage.
3. In the environment of temperature and moisture changing together, from section 6, we know that the influence of temperature on the decomposition rate is greater than the influence of moisture. It can be deduced that the relative advantages and disadvantages of combination 1 and combination 2 are mainly affected by the change of temperature. In the environment of large temperature change, combination 1 has relative advantage, while combination 2 has relative advantage only when the change of moisture is much greater than that of temperature.

7.3 Decomposition efficiency of fungi combinations

We believe that the diversity of fungi plays an important role in the decomposition efficiency of ground litter. By what we have analyzed, we find that as long as the fungi combinations can persist, the decomposition efficiency of the combinations is more stable than that of the single fungus in the combinations under different temperature and moisture changes. The reasons are as follows:

1. When there is a periodic long-term change

Due to the long-term fluctuations of the environment, the amplitude of change is relatively moderate. It can be considered as a relative steady state, i.e., after the temperature and moisture are initially determined, the temperature and moisture are constant. We know that the range of fungi RMCT ranking chart represents the sensitivity of single fungus to temperature change. By observing the ranking chart of fungi RMCT, it can be seen that once the potential fungi combinations are formed, the rank range of their combinations will be narrowed by taking the intersection. That makes the range of any combination is narrower than that of any component fungi in that combination. Thus, the sensitivity of combinations to temperature change is lower than that of single fungus to temperature change. That is to say, the potential fungi combinations have better temperature adaptability, and have relative advantage over any component fungus for large temperature change.

2. When there is a rapid short-term change

Due to the short-term rapid changes in the environment, the amplitude of change is more intense. It can be regarded as a huge change in the long run. We can draw a conclusion which is consistent with the long-term fluctuation of the environment, that is, the potential fungi combinations have better temperature adaptability, and have a relative advantage over the fungus in any combination under the environment of large short-term temperature change.

8. The effects of different natural environments on fungal competitions

Based on research (Climate of the United State, n.d.), we find the temperature and humidity data as shown below:

Table 2 The temperature and humidity in the given 5 environments

Environment Types	Temperature Range	Precipitation (Humidity)
Arid	2-32.2℃	380mm (-0.1±0.05MPa)
Semi-Arid	8-30℃	510mm (-0.3±0.15MPa)
Temperate	4-21℃	800mm (-0.6±0.4MPa)
Arboreal	0-16℃	400mm (-0.5±0.2MPa)
Tropical Rain Forest	21-32℃	2000mmm (-4±0.5MPa)

In all these five environments, our competition model is used to simulate the competition conditions under the long-term fluctuation of temperature and humidity for all fungi. The fungi are ranked by the relative competitiveness obtained by simulation. The top three and bottom three of each natural environment are listed in the table below:

Table 3 Adapted and unadaptable fungal species to different natural environments

Fungi with high adaptability	Environment Types	Fungi with low adaptability
Schizophyllum commune TJV93 5 A10A *Phlebiopsis flavidoalba FP150451 A8G* *Hyphoderma setigerum HHB12156 B3H*	Arid	*Armillaria gallica FP102531 C6D* *Armillaria gallica FP102534 A5A* *Armillaria gallica FP102535 A5D*
Schizophyllum commune TJV93 5 A10A *Schizophyllum commune PR1117* *Phlebiopsis flavidoalba FP150451 A8G*	Semi-arid	*Armillaria gallica FP102534 A5A* *Armillaria gallica FP102531 C6D* *Armillaria gallica FP102535 A5D*
Laetiporus conifericola HHB15411 C8B *Phlebiopsis flavidoalba FP150451 A8G* *Merulius tremellosus FP150849 C3F*	Temperate	*Armillaria gallica FP102535 A5D* *Armillaria gallica HHB12551 C6C* *Armillaria gallica SH1 A4A*
Hyphoderma setigerum HHB12156 B3H *Phlebiopsis flavidoalba FP150451 A8G* *Phlebia acerina MR4280 B9G*	Arboreal	*Armillaria gallica FP102542 A5B* *Armillaria gallica HHB12551 C6C* *Armillaria gallica SH1 A4A*
Pycnoporus sanguineus PR SC 95 A11C *Phlebiopsis flavidoalba FP150451 A8G* *Phlebiopsis flavidoalba FP102185 B12D*	Tropical	*Armillaria gallica FP102531 C6D* *Armillaria gallica FP102534 A5A* *Armillaria gallica FP102535 A5D*

Among them, it can be found that different natural environments have relatively low influence on the *Phlebiopsis flavidoalba FP150451 A8G*, i.e., it adapts to any of the above natural environments; arid and semi-arid environments have relatively low influence on the *Schizophyllum commune TJV93 5 A10A*, i.e., it adapts to arid and semi-arid environment, but does not quite adapt to other natural environments.

By observing the fungi that are not adapted to different natural environments, it is obvious that different natural environments have little effect on all fungi belonging to *Armillaria gallica*, that is, all fungi of *Armillaria gallica* are not adapted to any of the above natural environments (The detailed RMCT is in Appendix B).

How does Fungi make Contributions in Carbon Cycle?

The carbon cycle is one of the most crucial material circulations on earth. It plays a significant role both in nonliving world and biosphere including ecological systems. Fungi, as the main decomposer, actively participate in the carbon cycle by decomposing animal and plant debris including wood fibers.

Major influential factors for fungus' decomposition rate

The fungi decomposition rate could vary to a large extent among different fungi species. Besides, it could be sensitive to many environmental factors. According to the recent research, there are two major traits of fungi which could largely affect the decomposition rate: fungus growth rate and ambient humidity.

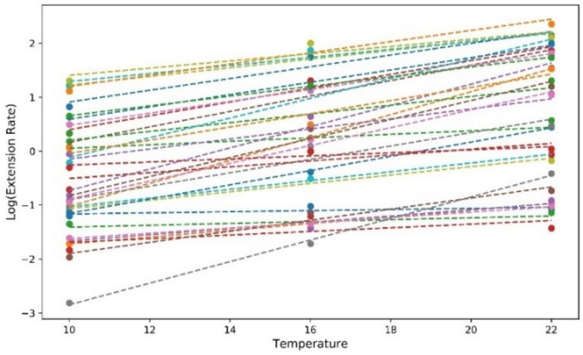

Figure 1 The correlation between temperature and growth rate of 34 species of fungi

Moreover, fungus growth rate has a positive correlation with the ambient temperature. We can obtain the relationship in Figure 1.

In addition, for each fungus species, the decomposition rate is related to its moisture tolerance. In other words, when the environmental moisture changes, fungi decomposition rate could be largely influenced.


Figure 2 Fungi decomposition on the wood fibers in a wet environment

Further, recent research has found that the product of fungus's growth rate and moisture tolerance is positively correlated to its decomposition rate.

$$D \propto f \cdot g$$

where f represents the growth rate, g represents the moisture tolerance and D represents the decomposition rate of fungi. Hence for each fungi species, its decomposition rate is sensitive to the temperature and humidity changes in the environment.

Trends between fungi' species

There is always competition between any two of fungi species. Based on the recent research, there are two types of trends for the relationship between two fungi' species: Competitive and long-term competitive symbiosis (see Figure 3 and Figure 4). If the two fungi are competitive symbiosis (Figure 3), it means that those two fungi have similar contribution to the carbon cycle. If the two are competitive (Figure 4), it means that only one of the fungi is taking the lead of influencing the carbon cycle.

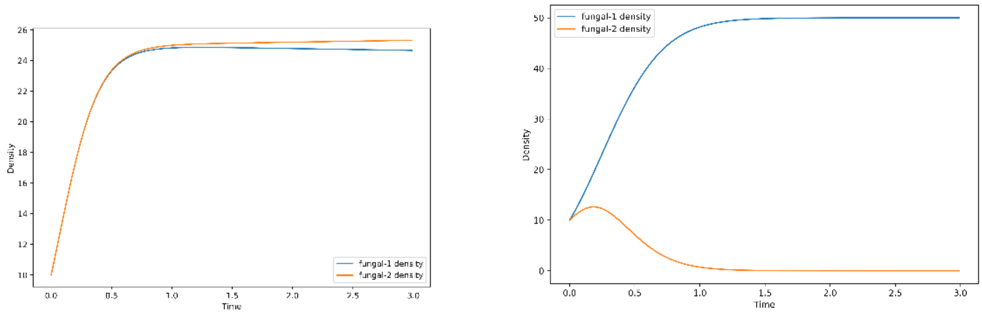

Figure 3,4 The symbiosis trend between two fungi (left) The competitive relationship between two fungi (right)

The relative advantages and disadvantages of fungi species combinations

Some of the fungi can be competitive symbiosis in specific temperature and humidity, for example, *Phlebia acerina MR4280 B9G* and *Phlebia acerina DR60 A8A*, *Armillaria sinapina PR9* and *Phellinus robiniae AZ15 A10H Banik/Mark*. Comparing to fungi that play a dominant role in carbon cycling, the increased biodiversity of fungal can reduce the sensitivity of the group to the temperature and humidity. However, those fungi species groups also have its weakness, that is, it would easily be defeated by other most-competitive fungi.

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Appendix A The notation of 34 fungi and its related color in Figure 1

- Armillaria gallica FP102531 C6D - V1
- Armillaria gallica EL8 A6F - V2
- Armillaria gallica FP102534 A5A - V3
- Armillaria gallica FP102535 A5D - V4
- Armillaria gallica FP102542 A5B - V5
- Armillaria gallica HHB12551 C6C - V6
- Armillaria gallica OC1 A6E - V7
- Armillaria gallica SH1 A4A - V8
- Armillaria sinapina PR9 - V9
- Armillaria tabescens FP102622 A3C - V10
- Armillaria tabescens TJV93 261 A1E - V11
- Fomes fomentarius TJV93 7 A3E - V12
- Hyphodontia crustosa HHB13392 B7B - V13
- Hyphoderma setigerum HHB12156 B3H - V14
- Hyphoderma setigerum FP150263 B2C - V15
- Laetiporus conifericola HHB15411 C8B - V16
- Lentinus crinitus PR2058 C1B - V17
- Mycoacia meridionalis FP150352 C4E - V18
- Merulius tremullosus FP102301 C3E - V19
- Merulius tremellosus FP150849 C3F - V20
- Phlebiopsis flavidoalba FP102185 B12D - V21
- Phlebiopsis flavidoalba FP150451 A8G - V22
- Phellinus gilvus HHB11977 C4H - V23
- Phellinus hartigii DMR94 44 A10E - V24
- Porodisculus pendulus HHB13576 B12C - V25
- Phellinus robiniae FP135708 A10G - V26
- Phellinus robiniae AZ15 A10H Banik/Mark - V27
- Phlebia acerina MR4280 B9G - V28
- Phlebia acerina DR60 A8A - V29
- Pycnoporus sanguineus PR SC 95 A11C - V30
- Schizophyllum commune TJV93 5 A10A - V31
- Schizophyllum commune PR1117 - V32
- Tyromyces chioneus HHB11933 B10F - V33
- Xylobolus subpileatus FP102567 A11A - V34

Appendix B The edge effect of fungi in different environments

Name	Arid	Semi-arid	Temperate	Arboreal	Tropical
Armillaria gallica FP102531 C6D	0.013	0.011	0.079	0.145	0.009
Armillaria gallica EL8 A6F	0.025	0.023	0.044	0.086	0.036
Armillaria gallica FP102534 A5A	0.012	0.012	0.063	0.126	0.002
Armillaria gallica FP102535 A5D	0.001	0.002	0.035	0.078	0.001
Armillaria gallica FP102542 A5B	0.031	0.028	0.053	0.072	0.034
Armillaria gallica HHB12551 C6C	0.031	0.035	0.020	0.028	0.095
Armillaria gallica OC1 A6E	0.032	0.029	0.055	0.108	0.025
Armillaria gallica SH1 A4A	0.154	0.127	0.005	0.012	0.254
Armillaria sinapina PR9	0.133	0.124	0.152	0.105	0.146
Armillaria tabescens FP102622 A3C	0.141	0.131	0.156	0.229	0.162
Armillaria tabescens TJV93 261 A1E	0.254	0.224	0.154	0.241	0.348
Fomes fomentarius TJV93 7 A3E	0.550	0.369	0.197	0.276	0.902
Hyphodontia crustosa HHB13392 B7B	0.197	0.185	0.286	0.396	0.194
Hyphoderma setigerum HHB12156 B3H	0.826	0.713	0.517	0.757	0.846
Hyphoderma setigerum FP150263 B2C	0.644	0.524	0.281	0.186	0.901
Laetiporus conifericola HHB15411 C8B	0.734	0.626	0.798	0.724	0.861
Lentinus crinitus PR2058 C1B	0.644	0.523	0.332	0.717	0.749
Mycoacia meridionalis FP150352 C4E	0.314	0.273	0.197	0.327	0.378
Merulius tremullosus FP102301 C3E	0.558	0.451	0.503	0.646	0.826
Merulius tremellosus FP150849 C3F	0.596	0.518	0.525	0.685	0.808
Phlebiopsis flavidoalba FP102185 B12D	0.684	0.582	0.517	0.664	0.903
Phlebiopsis flavidoalba FP150451 A8G	0.876	0.755	0.682	0.757	0.955
Phellinus gilvus HHB11977 C4H	0.302	0.269	0.314	0.427	0.454
Phellinus hartigii DMR94 44 A10E	0.141	0.133	0.205	0.293	0.165
Porodisculus pendulus HHB13576 B12C	0.629	0.386	0.456	0.430	0.417
Phellinus robiniae FP135708 A10G	0.630	0.511	0.126	0.456	0.730
Phellinus robiniae AZ15 A10H Banik/Mark	0.406	0.340	0.207	0.292	0.633
Phlebia acerina MR4280 B9G	0.685	0.593	0.359	0.732	0.798
Phlebia acerina DR60 A8A	0.545	0.482	0.322	0.675	0.794
Pycnoporus sanguineus PR SC 95 A11C	0.668	0.554	0.346	0.478	1.001
Schizophyllum commune TJV93 5 A10A	0.990	0.883	0.475	0.398	0.825
Schizophyllum commune PR1117	0.825	0.841	0.462	0.303	0.641
Tyromyces chioneus HHB11933 B10F	0.489	0.425	0.449	0.611	0.674
Xylobolus subpileatus FP102567 A11A	0.171	0.157	0.253	0.377	0.128