Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
A		**2118366**

Simulation of Woody Fibers Decomposition by Fungal Colonies Based on Improved Monod Equation

Summary

The decomposition of woody fibers is a key component of the Earth ' s Carbon Cycle. Fungi are virtually the only organisms capable of breaking down lignin, one of the major constituents of woody fibers. Our goal is to build a model of fungal colony decomposing woody fibers to simulate the effects of environment and fungal types on the decomposition of woody fibers.Solving this problem will have great economic value.

On the one hand, in terms of describing the decomposition rate of woody fibers by fungal colonies with different characteristics, we used the multivariate nonlinear model to fit the functional expression of temperature, moisture, moisture tolerance of fungus and their density on the decomposition rate ; On the other hand, in terms of describing the interaction between different fungal colonies, the fungus extension rate and woody fibers decomposition rate were affected by environmental and climatic factors. We used the Monod equations model with inhibitory factors to simulate the environmental adaptability of various fungi.

In the multivariate nonlinear model, we combined a large number of experimental data of woody fibers decomposition by fungal colonies. It is on the basis of these data that we have achieved good results in the fitting process. At the same time, in order to more accurately reflect the impact of environmental and climatic factors on fungal colonies, we also collected relevant environmental and climatic data.

The solution we proposed simulates the growth of various fungi and the decomposition of woody fibers in a changing environment. It can reflect the growth rate of fungi and decomposition rate at all times, as well as the interaction between different fungi. And from the simulation results, it can be seen that the characteristics of the fungus and the environment affect this process. In addition, by controlling the variable of fungal species, we can also derive the role of fungal diversity.

Keywords: fungi; Monod equation; multivariate nonlinear fitting; woody fibers

Contents

1 Introduction

1.1 Problem Background

The decomposition of plant materials and woody fibers is an important part of the Earth ' s carbon cycle. It significantly affects soil respiration and is the basis of forest soil material conversion. It plays an indispensable role in promoting material cycle, nutrient balance and maintaining the functions of forest ecosystems. A key factor in decomposing woody fibers is fungi.

With the increasing proportion of woody fibers components in municipal solid waste, such as waste paper, waste fiber and sawdust, the composting reaction time is long, the maturity is insufficient, and the particle size of the product is large, which leads to the low economic value of the compost product and the lack of market competitiveness.

A key factor in woody fibers degradation is fungi. Therefore, it is necessary to study the influencing factors of fungal decomposition rate of woody fibers.

1.2 Analysis of the Problem

Fungi decomposition rate of woody fibers is related to many factors, the internal factors are moisture tolerance, hyphal extension rate, fungi density, external factors are temperature, moisture, etc. A variety of fungi interact with each other during the decomposition of woody fibers. We are going to establish the following models.

1.2.1 A mathematical model to describe the decomposition of ground litter and woody fibers by multiple species of fungi

According to data in the references[3][8] :

- Moisture niche width (MPa)(which means range where hyphal extension rate $\geq 50\%$ of the maximum rate)
- Competitive ranking
- Hyphal density of each fungus(ug biomass cm^{-2})
- The decomposition rate (mass loss$\%$within 122 days) by various fungi which are measured for each isolate under standardized laboratory conditions at 10,16 and 22°C

- The hyphal extension rates which are measured at different temperatures and different moisture conditions

We can fit an equation about temperature, moisture, moisture tolerance (the competitive ranking of each isolate and the difference in their water niche width), hyphal density, hyphal extension rate, and decomposition rate. Then we can describe the average rate of woody fibers decomposition by a fungus in a period of time.

It should be noted that the meaning of moisture mentioned in this paper is soil water potential, because we study the decomposition of woody fibers on the ground. Soil water potential is the energy needed to extract unit water from soil under isothermal conditions, unit is MPa. When the soil moisture is saturated, the water potential is zero ; When water content is lower than saturated state, water potential is negative ; The more dry the soil, the greater the negative value.

1.2.2 The model with interaction of different types of fungi

Different fungi have different growth and decomposition rates, as well as different products. Under constant external conditions, the growth rate and decomposition rate of a fungus are influenced by the mass of the reactant woody fibers, and its own mass. In addition, the products of the fungus may have an effect on itself or other fungi, usually an inhibitory effect. Taking these factors into consideration, we can develop a set of differential equations to describe the dynamic process of woody fibers decomposition by various fungi.

1.2.3 A model of fungi decomposition of woody fibers in changing external environment

According to the statistical weather data, we can obtain the variation trend and range of moisture and temperature in different climate environments. Based on this, a roughly moisture and temperature function can be fitted and substituted into the differential equation group of fungal interaction and woody fibers decomposition, and a new differential equation group can be obtained. By solving this differential equation group, the decomposition of woody fibers by fungi in a specific climate environment can be obtained.

2 Assumptions

To simplify the given problems, we make the following assumptions for our models.

- In the case of sufficient woody fibers and oxygen, the decomposition rate of woody fibers by a single kind of fungus is only affected by the following factors: growth rate, moisture tolerance, temperature and moisture.
- Fungi growth and decomposition of ground litter in the fixed patch of land do not lead to changes in environmental moisture and temperature.
- In these different environments including arid, semi-arid, temperate, arboreal, and tropical rain forest, only the differenece in temperature and moisture are considered.
- Woody fibers decomposition is only affected by fungi, no other microorganisms have an effect on it.

3 Notations

We list the symbols and notations used in this paper in Table 1.

Table 1: Notation

Symbols	Definition
v_h	Hyphal extension rate (mm/day)
v_d	Decomposition rate ($\%$ mass loss over 122 days)
T	Temperature
w_n	Moisture tolerance(scaled to $[-1, 1]$)
ρ	Hyphal density of fungi(ug biomass cm^{-2})
w	Moisture (MPa)
S	The mass of woody fibers
x_i	The mass of fungus i
y_i	The mass of woody fibers consumed by fungus i
t	Reaction time (day)
$\mu_{\max}^i$	Maximum rate of decomposition of fungus i
K_s^i	Saturation constant of fungus i
Y	Yield coefficient
a_i	Mortality rate of fungi i
η_j^i	The ratio of harmful substances to fungal i in the products of fungal j to consumed reactants of fungal j
b_j^i	Inhibitory effect ratio of harmful substances in fungal j on fungal i

4 The model

4.1 Decomposition rate model

The decomposition rate is related to many fungi traits and external environment factors. We mainly study the relationship between the decomposition rate and five factors: the hyphal extension rate, moisture tolerance, hyphal density of fungi, temperature and moisture.

- **Effect of moisture tolerance and hyphal density of fungi on hyphal extension rate**

  We explored moisture tolerance and hyphal density of fungi to determine hyphal extension rate of the fungi. By fitting the data(reference 1), we found that when the temperature is 22 °C and the moisture is -0.5 MPa, the moisture tolerance, hyphal density and hyphal extension rate could meet the following equation. Moisture tolerance is limited between -1 and 1.

$$\log(v_h) = 0.21 - 0.40w_n^2 + 2.98w_n - 1.06\rho + 0.59\rho^2 - 1.64w_n\rho \tag{1}$$

  R-square is 0.7693.

- **Effect of temperature, humidity, moisture tolerance and hyphal density of fungi on hyphal extension rate**

  We assume that the hyphal extension rate satisfies the following relation.

$$\log(v_h) = a_0 + a_1T + a_2T^2 + a_3w + a_4w^2 + a_5w_n^2 + a_6w_n + a_7\rho + a_7\rho^2 + a_8w_n\rho \tag{2}$$

Substitute the data and then we can get the relation.

$$\begin{aligned}\log(v_h) =&282.96 - 1.96T + 0.003T^2 - 1.47w^2 - 0.007Tw + 2.92w_n \\ &- 0.47w_n^2 - 0.90\rho + 0.49\rho^2 - 1.57w_n p\end{aligned} \quad (3)$$

R-square is 0.8009.

- **The relationship between decomposition rate and the hyphal extension rate**
According to relevant data, we have plotted the relationship between decomposition rate and hyphal extension rate which shows the growth rate of fungi at various temperature, as shown in Figure 1. In this set of data, the percentage of wood decomposed in 122 days represents the rate of decompositon. Except for these two variables and temperature, everything else is constant. As can be seen from this figure, the decomposition rate increases with the hyphal extension rate. Based on these data, we fit the relationship between decompotion rate($\%$ mass loss over 122 days) and hyphal extention rate(mm/day).

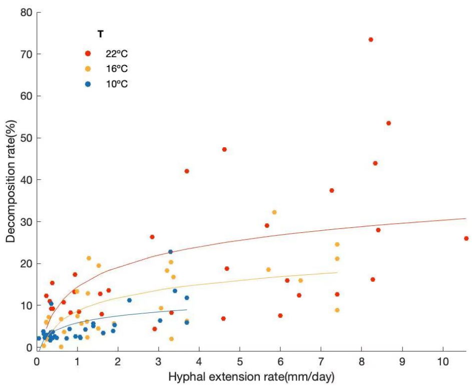


Figure 1: the relationship between decomposition rate and the growth rate

At three temperatures, the fitted equations are

$$v_d = 5.8414 + 2.3854\log(v_h) \quad T = 295K \quad (4)$$

$$v_d = 8.6425 + 4.5941\log(v_h) \quad T = 289K \quad (5)$$

$$v_d = 14.3908 + 6.9381\log(v_h) \quad T = 283K \quad (6)$$

- **Effect of temperature, hyphal extension rate on decomposition rate**

We explored temperature, hyphal extension rate to determine the resulting wood decomposition rate. By fitting the data, We can get the relationship in equation (8) and plot the figure as shown in Figure 2.

$$v_d = 3647.43 - 15.06v_h - 0.0297v_h^2 - 25.77T + 0.0455T^2 + 0.0615v_hT \quad (7)$$

R-square is 0.5203.

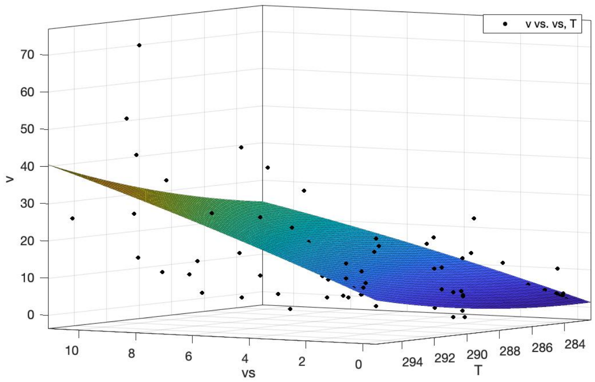


Figure 2: Effect of temperature, hyphal extension rate on decomposition rate

In summary, we obtained the equation of hyphal extension rate and the equation of decomposition rate.

$$\begin{aligned}\log(v_h) =&282.96 - 1.96T + 0.003T^2 - 1.47w^2 - 0.007Tw + 2.92w_n \\ &- 0.47w_n^2 - 0.90\rho + 0.49\rho^2 - 1.57w_n p\end{aligned} \tag{8}$$

$$v_d = 3647.43 - 15.06v_h - 0.0297v_h^2 - 25.77T + 0.0455T^2 + 0.0615v_h T \tag{9}$$

4.2 Kinetic model of woody fibers decomposition by various fungi

There is a Monod equation[4] in microbial dynamic, which reflects the dynamic process of a single microorganism in a bacth reactor. X is the microbial mass, S is the mass of reactants, Y is the yield coefficient, $\mu_{\max}$ is the maximum specfic growth rate, and K_s is the saturation constant. The equation is as follow.

$$\frac{dX}{dt} = \mu_{\max}\frac{XS}{K_s + S} \tag{10}$$

$$\frac{dS}{dt} = -\frac{\mu_{\max}}{Y}\frac{XS}{K_s + S} \tag{11}$$

This equation can just reflect the case of a single species, and does not take into account multiple factors such as microbail mortailty.

Considering the breakdown of ground litter and woody fibers through fungal activities in the presence of multiple species of fungi. Under different external environment, the correlation coefficient of each fungus is different. μ_{max}, K_s and Y are determined by inernal factors and external factors.

The rate at which each fungus decomposes woody fibers is as follow.

$$\frac{dy_i}{dt} = \frac{\mu^i_{\max}}{Y_i}\frac{x_i S}{K^i_s + S} \tag{12}$$

The rate of change of each fungal mass is as follow.

$$\frac{dx_i}{dt} = \mu_{\max}^i \frac{x_i S}{K_s^i + S} - a_i x_i - \sum_j b_j^i(\eta_j^i y_j)x_i \tag{13}$$

The rate of decomposition of woody fibers is as follow.

$$\frac{dS}{dt} = -\sum_i \frac{dy_i}{dt} \tag{14}$$

Therefore, we can estabilish a differential equation system for the decomposition of woody fibers by various fungi.

$$\begin{cases} \dfrac{dy_i}{dt} = \dfrac{\mu_{\max}^i}{Y_i} \dfrac{x_i S}{K_s^i + S} \\ \dfrac{dx_i}{dt} = \mu_{\max}^i \dfrac{x_i S}{K_s^i + S} - a_i x_i - \sum_j b_j^i(\eta_j^i y_j)x_i \\ \dfrac{dS}{dt} = -\sum_i \dfrac{dy_i}{dt} \end{cases} \tag{15}$$

4.3 Kinetic model of woody fibers decomposition by the fungi of different traits in different environment

In equation (16), parameters Y_i and $\mu_{\max}^i$ are determined by the characteristics of each fungus and environmental factors. We can determine these parameters based on the model in 4.1.

The decomposition rate model determines woody fibers decomposition rate and growth rate in 122 days under certain conditions. This is the average rate, not the instantaneous rate. We can determine the parameters Y_i and $\mu_{\max}^i$ based on these two quantities and the initial quantities set by the model.

From equation (11) and (12), we can deduce the following relations.

$$\frac{dS}{dt} = -\frac{1}{Y}\frac{dX}{dt} \tag{16}$$

$$Y = \frac{|\Delta X|}{|\Delta S|} \tag{17}$$

This Y not only reflects the ratio of growth rate and decomposition rate of fungi, but also contains the coefficient of unit conversion.

According to the v_h and v_d in the decomposition rate model, we can get the formula of Y.

$$Y = \frac{v_d}{v_h} \tag{18}$$

According to the integral formula [4] derived from differential equations (11) and (12), we can calculate the parameter $\mu_{\max}$.

$$\mu_{\max} = (1 + \frac{K_s Y}{S_0 Y + X_0}) \ln[1 + \frac{Y}{X_0}(S_0 - S)] - \frac{K_s Y}{S_0 Y + X_0} \ln[\frac{S}{S_0}] \tag{19}$$

S_0 and X_0 have been shown in the reference, S can be derived from v_d and S_0.

Other coefficients K_s^i, a_i , b_j^i and η_j^i can be obtained from the relevant literature. We also ignore the influence of external circumstances on these parameters.

4.4 Kinetic model of fibers decomposition by different fungi in a constantly changing external environment

When the external environment changes, w, T, as a function of t, is substituted into the model of extension rate and decomposition rate to get the function $v_h(t)$ and $v_d(t)$. When determining the moisture tolerance and hyphal density of fungi, they are univariate functions about t. Then according to the method in 4.3, we can get $Y(t)$, $\mu_{\max}(t)$. Substituting them into equation (16), a new differential equation system can be obtained.

$$\begin{cases} \dfrac{dy_i}{dt} = \dfrac{\mu_{\max}^i(t)}{Y_i(t)} \dfrac{x_i S}{K_s^i + S} \\ \\ \dfrac{dx_i}{dt} = \mu_{\max}^i(t) \dfrac{x_i S}{K_s^i + S} - a_i x_i - \sum\limits_j b_j^i (\eta_j^i y_j) x_i \\ \\ \dfrac{dS}{dt} = -\sum\limits_i \dfrac{dy_i}{dt} \end{cases} \tag{20}$$

5 Calculating the Model and the Model Results

5.1 Interaction of different fungi and decomposition of woody fibers by these fungi in a constant environment

5.1.1 Condition in which fungi do not produce inhibitory substances

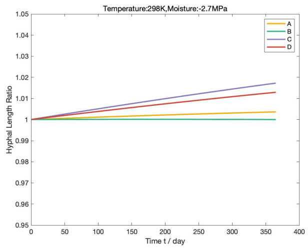
In our model, the fungal characteristics that affect the decomposition rate and growth rate of fungi are moisture tolerance and hyphal density. According to these two characteristics, we divide fungi into four categories, as shown in Table 2. Fungus A has low moisture tolerance and high hyphal density, Fungus B has low moisture tolerance and low hyphal density, Fungus C has high moisture tolerance and low hyphal density, Fungus D has high moisture tolerance and high hyphal density. They do not refer to specific fungi, but have typical shapes. And we assume that fungi do not produce substances that inhibit their own and other fungal activities.

Then we bring it into the model in 4.3 to simulate. In order to control the variable, the parameters a_i take the same appropriate value, the parameters b_j^i and η_j^i take zero. We simulated the decomposition of woody fibers and the growth of fungi in a year, without considering the changes of the external environment. The results are shown in the Figure 3, 4, 5, 6. The ordinate in the figure : hyphal length ratio refers to the ratio of the hyphal length at time t to the hyphal

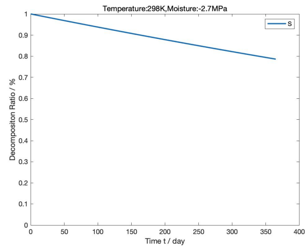
	A	B	C	D
moisture tolerance	-0.5	-0.5	0	0
hyphal density	1	0.3	0.3	1

Table 2: The moisture tolerance and hyphen density of different fungi

length at time 0, and decomosition ratio refers to the ratio of the content of woody fibers at time t to the content of woody fibers at time 0.

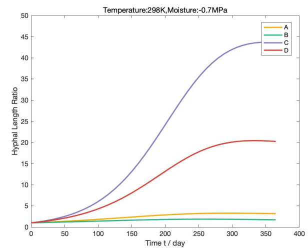


(a) the extension of mixed four fungi

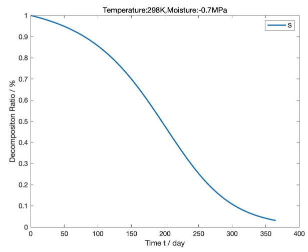


(b) Decomposition of woody fibers

Figure 3: the condition with temperature of 298K and moisture of -2.7MPa

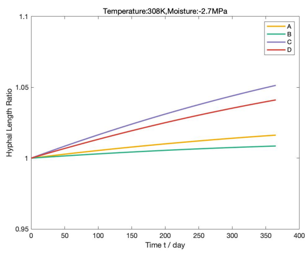


(a) The extension of mixed four fungi

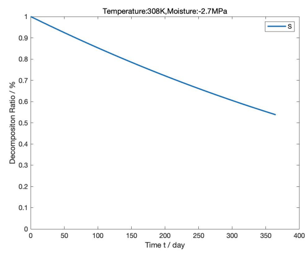


(b) Decomposition of woody fibers

Figure 4: the condition with temperature of 298K and moisture of -0.7MPa



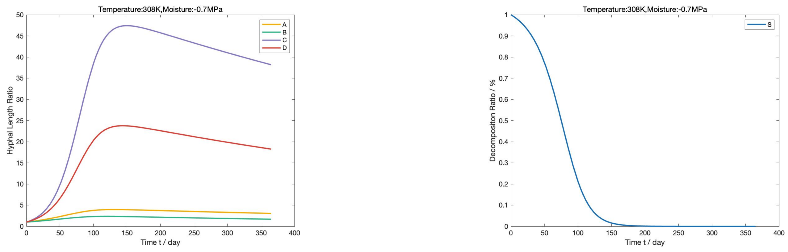
(a) The extension of mixed four fungi



(b) Decomposition of woody fibers

Figure 5: the condition with temperature of 308K and moisture of -2.7MPa

It can be seen from these four groups of simulations that fungus C has the strongest adaptability in various environments, indicating that high moisture tolerance and low hyphal density



(a) The extension of mixed four fungi

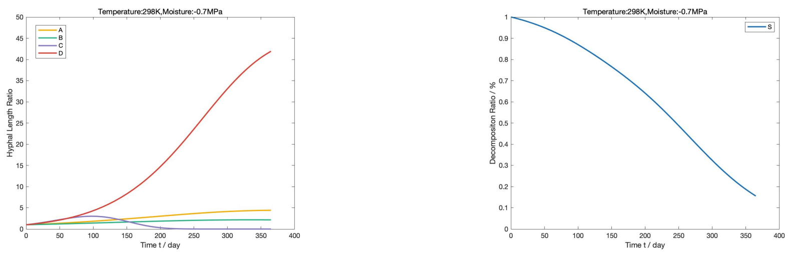
(b) Decomposition of woody fibers

Figure 6: the condition with temperature of 308K and moisture of -0.7MPa

are conducive to fungal survival and woody fibers decomposition. And when each fungus has similar mortality rates and does not produce harmful substances to its survival, competition among fungi inhibits the growth of fungi with weak viability. In these environments, when the temperature is 308K and the moisture is-0.7MPa, the fungi growth rate and decomposition ability of fungi are the strongest.

5.1.2 Condition in which fungi produce inhibitory substances

A fungus may be inhibited by substances produced by other fungi. In order to study the effect of this inhibition, we still selected four fungi A, B, C and D, and set the same mortality rate of these fungi for simulation under the environment of 298K and -0.7MPa. Different from the simulation in 5.1.1, parameters b_j^C and η_j^C are set to a positive value, which means that fungus C will be inhibited by other fungi, and then we simulated the result as shown in Figure 7.



(a) The extension of mixed four fungi

(b) Decomsition of woody fibers

Figure 7: the condition with temperature of 298K and moisture of -0.7MPa

It can be seen from the figure that the dominant fungus C in the absence of inhibition, in the simulation of this condition, still maintain a rapid growth at the beginning, but when it and D grow to a certain extent, it will begin to decrease. So when some fungi grow faster than other fungi, they may produce some substances or inhibit other fungi in other ways to improve their competitiveness.

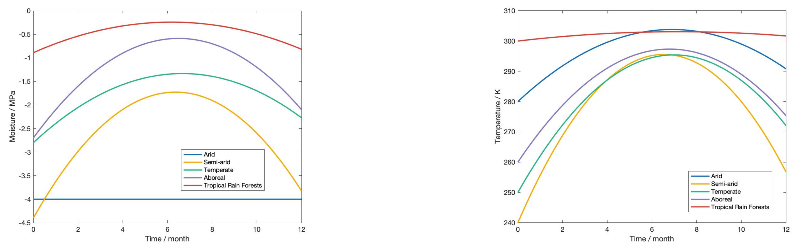
5.2 Interaction of different fungi and decomposition of woody fibers by these fungi in a constantly changing external environment

The following simulations of fungi A, B, C, D are in a changing environment, each simulation set the same parameters a_i, b_j^i, η_j^i. The parameters a_i, b_j^i, η_j^i between fungi are similar values.

5.2.1 Simulation in Several Typical Environments

In order to study the survival status of fungi and the decomposition of woody fibers in different environments, we selected several typical climates, such as arid, semi-arid, temperature, arboreal and tropical rain forests.

We searched the temperature and moisture data of these climatic conditions and fitted the function of temperature and moisture of each climatic condition with respect to time in a year. The images are shown in Figure 8.



(a) Relationship between moisture and time

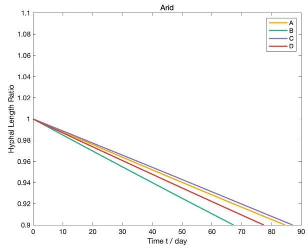
(b) Relationship between temperature and time

Figure 8: Temperature and moisture function images of several climate types

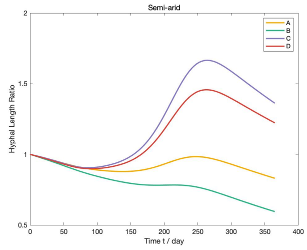
Then under these climate types, we simulated the decomposition of woody fibers by fungi and the growth of fungi, as shown in Figure 9.

From these pictures we can see that

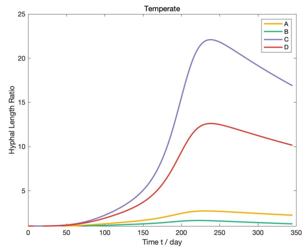
- under arid condition, fungi are difficult to survive.
- In the semi-arid environment, due to the changes in moisture and temperature, the growth of fungi is first inhibited in a relatively dry and low temperature environment, and then around July, the growth rate was the highest, and then the survival is inhibited due to environmental changes and the reduction of woody fibers causing the reduce of amount.
- In the temperate environment, the moisture is more suitable, so the activity of the fungi is mainly affected by temperature changes. The temperature gradually increases in the first half of the year. When the temperature becomes more suitable and the food is sufficient, the grouwth rate of the fungi increases rapidly, until August Around that time, the amount of fungi reached a peak, and after that, the amount of fungi began to decrease due to food consumption.
- In the arboreal environment, the moisture change trend and the temperature change trend are similar to those of the temperate, but the overall moiture is higher than that of the temperate, and the temperature is close to that of temperate. Therefore, the trend of the growth image of fungi is very close to the situation in temperate, but the growth rate is higher than that in temperate.
- In the environment of tropical rain forests, the temperature and moisture do not change much and are more suitable for the survival of fungi. Therefore, the fungi grow rapidly from the beginning to decompose woody fibers. Woody fibers are consumed quickly, so the amount of fungi reaches a peak soon, and due to insufficient food, it drops rapidly.



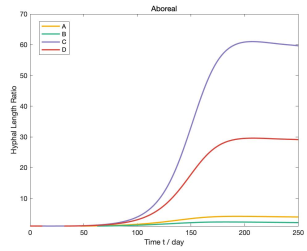
(a) Growth of fungi in arid



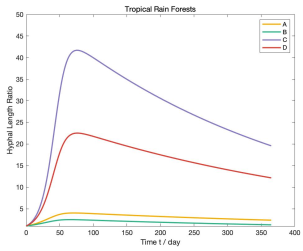
(b) Growth of fungi in semi-arid



(c) Growth of fungi in temperate



(d) Growth of fungi in arboreal



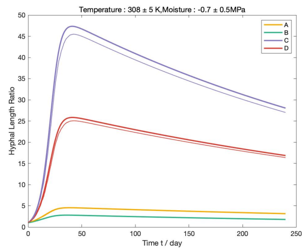
(e) Growth of fungi in tropical rain forests

Figure 9: Grouth of fungi in different climate types

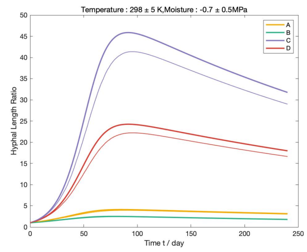
5.2.2 Sensitivity of model to rapid fluctuations in the environment

We select four environments in 5.1.1 and add a random fluctuation over time to these four environments, getting the simulation results as shown in Figure 10. In (a) and (b), coarse lines refer to the hyphal length when the climate is constant, and fine lines refer to the hyphal length when the climate is fluctuating.

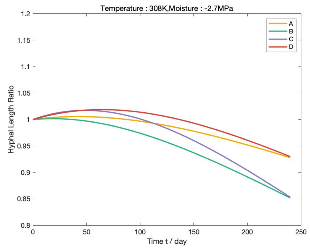
As can be seen from the figure, when the temperature is 308K and the moisture is -0.7MPa, small-scale climate fluctuations have little effect on fungal growth activity. But when the temperature is 308K and the moisture is -2.7MPa, small-scale climate fluctuations have a greater impact on fungal grouth activity. Under this climate condition, if the environment is constant, the final survival of A is better than C, but with a random fluctuation, the final survival of A is worse than C. In the other two cases, climate fluctuations have a certain impact. Thus we can see that under different climate conditions, there are different sensitivities to rapid fluctuation. At 308 K and -0.7 MPa, fungal survival and decomposition ability is strong, small range of climate fluctuations will not have a great impact. In this environment, fungi have strong adaptability.



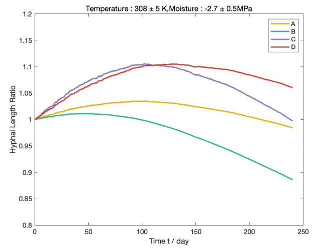
(a) the case of constant climate and the case of climate fluctuations in temperature 308K and moisture -0.7MPa



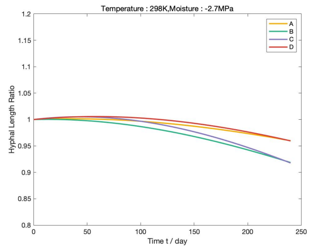
(b) the case of constant climate and the case of climate fluctuations in temperature 298K and moisture -0.7MPa



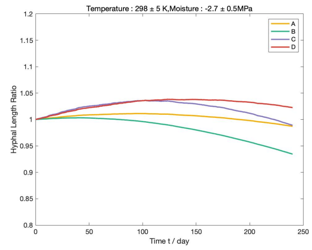
(c) the case of constant climate in temperature 308K and moisture -2.7MPa



(d) the case of climate fluctuations in temperature 308K and moisture -2.7MPa



(e) the case of constant climate in temperature 298K and moisture -2.7MPa



(f) the case of climate fluctuations in temperature 298K and moisture -2.7MPa

Figure 10: the contrast of the case of constant climate and the case of climate fluctuations

5.3 The effect of fungal diversity on the decomposition of woody fibers

In order to study the influence of fungal diversity on woody fibers decomposition, we selected fungi with the following characteristics, as shown in Table 3.

	1	2	3	4	5	6	7	8
moisture tolerance	-0.25	-0.3	-0.2	-0.35	-0.15	0.4	-0.1	-0.5
hyphal density	0.5	0.45	0.55	0.4	0.6	0.35	0.7	0.3

Table 3: The moisture tolerance and hyphal density of different fungi

Then we select fungi to combine, D is the combination of fungi 1,2,3,4,5,6,7 and 8; C is the combination of fungi 1,2,3,4,5 and 6; B is the combination of fungi 1,2,3 and 4; A is the combination of fungi 1 and 2. Then we simulated the growth of fungi and got the following results, as shown in the Figure 11.

It can be seen from the simulation results that the diversity of fungi does not particularly affect the results at the beginning, but in the later stage, the more fungi species, the stronger the decomposition of woody fibers.

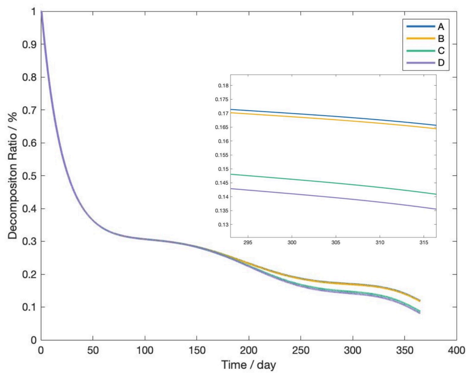


Figure 11: the relationship between decomposition rate and the growth rate

6 Evaluation of the Model and Conclusion

6.1 Strengths and weaknesses

6.1.1 Strengths

- In the references[3][8], we found a large number of experimental data on woody fibers decomposition by fungi. On this basis, combined with the changes of temperature and moisture, the extension ratio of fungi and woody fibers decomposition ratio were fitted. The equation of extension ratio of fungi with respect to temperature, moisture, moisture tolerance and the density of fungus showed R-square is 0.8009, which had good fitting effect.

- When we deal with the woody fibers decomposition by a variety of fungi, we use the characteristics of a single substrate to skillfully combine the Monod equation, which describes the process of woody fibers degradation by one or more fungi. At the same time, we further improve the Monod equation by adding the death factors of fungus and the possible inhibitory factors when a variety of fungi coexist, so that the final simulation results are more in line with the relevant experimental data.

6.1.2 Weakness

- Due to the diversity of fungi and the complex relationship between them, it is difficult to express them in a more intuitive way, so there may be some errors when considering the problem.
- When solving the improved Monod equation, the specific equation function cannot be obtained. We adopt the method of numerical solution in the simulation of this paper, which lacks rigorous description of the conclusion.

6.2 Conclusion

- We combined with the reference on a variety of fungi at different temperatures of woody fibers decomposition rate, and the corresponding woody fibers decomposition rate under different moisture tolerance data. The obtained data were fitted by multivariate nonlinear fitting, and the functional relationship between temperature and fungus extension rate on woody fibers decomposition rate was obtained in a certain range.
- We combine the moisture tolerance of woody fibers decomposition data. Similarly, these data were subjected to multivariate nonlinear fitting to obtain the woody fibers decomposition rates of various fungi at different temperatures and different moisture tolerances.
- We set four different types of fungus according to their moisture tolerance and density. Considering the possible competitive relationship between various fungi, We added a restraining factor on the basis of Monod equation, combined with the functional relationship obtained from the previous two problems, we can obtain the growth rate of various strains. In the analysis of sensitivity to detect rapid environmental fluctuations. We set multiple sets of different initial environments to conduct small disturbances on temperature and moisture. The stability of these fungi was obtained from the fungus extension rate.
- On the basis of the third question, we looked for the temperature and moisture data corresponding to arid, semi-arid, temperate, arboreal and tropical rain forests climate throughout the year. Combined with these data, the improved Monod equation was used to simulate the fungus extension rate of various fungus to analyze their relative advantages and disadvantages.
- For different environments, we tried various fungal combinations of different types. By comparing the decomposition rate of woody fibers under the action of these different fungal combinations at the same time, it is concluded that the decomposition rate of woody fibers will increase when the fungi are more abundant.

References

[1] HUANG D Y, LU W G, WANG H T, Microbiological mechanism of organic solid waste composting treatment[J] Techniques and Equipment for Environmental Pollution Control 2004.1 Vol.5 No.1 12 18

[2] LU Q Q, HUANG G Q. Microbial dynamics optimization algorithm[J]. Journal of Frontiers of Computer Science and Technology, 2019, 13(9): 1567-1581.

[3] Nicky Lustenhouwer, Daniel S. Maynard, Mark A. Bradford, Daniel L. Lindner, Brad Oberle, Amy E. Zanne, Thomas W. Crowther. A trait-based understanding of wood decomposition by fungi[J]. Proceedings of the National Academy of Sciences,2020(prepublish).

[4] SUN W, ZENG G M, WEI W Z, HUANG G H, WEI A L.Comparison of new parameter estimation algorithms for microbial degradation kinetics [J].Journal of Hunan University (Natural Science Edition), 2006 (05) : 114-119.

[5] WANG Y Z, Dynamic Analysis of a Kind of Microbial Model[J]Jounal of Neijiang Normal University 2020.12 Vol.35 No.12 37 40

[6] XI B D, LIU H L, BAI Q Z, HUANG G H, ZENG G M, LI Y J,Research status on biodegradation of cellulose and lignin in composting[J] Techniques and Equipment for Environmental Pollution Control 2002.3 Vol.3 No.3 19 23

[7] ZHANG X H, R.Bajpai, Analysis of Kinetic Model of Microbial Co-degradation[J]acta scient iar circumstan tiae 2000.9 Vol .20, Suppl 58 63

[8] https://github.com/dsmaynard/fungal_biogeography

Appendices

Appendix A First appendix

Calc

```
function [u,Y] = calc(T,w,wn,p)
%%
%  This function is used to calculate u, Y, where T ? temperature ;
%w ? humidity ; wn ? moisture resistance ; p ? density ;
%% š-ş
v_s = exp(282.959915141053-1.95521061447133*T+0.00337180876031599*T^2
-1.47293435022412*w^2-0.00713113748761690*T*w+...
2.91753499924237*wn-0.465040145080047*wn^2-0.903916432305213*p+
0.493345082635347*p^2-1.57574034551470*wn*p);
v = 3647.43425238583-15.0612270364577*v_s-0.0297245543546464*v_s^2
-25.7664799039810*T+0.0455349312806858*T^2+0.0614681517176178*v_s*T;
S_0 = 20000;
X_0 = 8000;X = X_0+v_s*122;
Y = 122*v_s/v;K_s = 50000;
u = (1+K_s*Y/(S_0*Y+X_0))*log(X/X_0)-K_s*Y/(S_0*Y+X_0)*log(1-(X-X_0)/S_0/Y);
```

Cupt2

```
%% Initialization of parameters
start_t = 0;end_t = 122;
S_0=20000;X_0=8000;
x1_0=X_0/4;x2_0=X_0/4;x3_0=X_0/4;x4_0=X_0/4;
y1_0=0;y2_0=0;y3_0=0;y4_0=0;
%%
[t,d] = ode45(@function_2,[start_t end_t],
[S_0;x1_0;x2_0;x3_0;x4_0;y1_0;y2_0;y3_0;y4_0]);
d(:,1) = d(:,1)/S_0;
d(:,2) = d(:,2)/x1_0;
d(:,3) = d(:,3)/x2_0;
d(:,4) = d(:,4)/x3_0;
d(:,5) = d(:,5)/x4_0;
plot(t,d(:,2),'r-*',t,d(:,3),'g-*',t,d(:,4),'m-*',t,d(:,5),'y-*');
%plot(t,d(:,1),'-*');
title('Temperature:298K,Moisture:-0.7MPa,');
xlabel('Time t');
ylabel('Hyphal Length Ratio');ylim([0.97,1.03]);
%ylabel('Decompositon Ratio');ylim([0,1]);
%legend('S');
legend('A','B','C','D');
```

Function2

```
function D = function_2(~,d)
D = zeros(9,1);
%% Initialization of parameters
K_x = 50000;T = 298;w = -2.7;
[u1,Y1] = calc(T,w,-0.5,1);
[u2,Y2] = calc(T,w,-0.5,0.2);
[u3,Y3] = calc(T,w,0,0.3);
[u4,Y4] = calc(T,w,0,1);
a1=0;a2=0;a3=0;a4=0;
%a1 = 0.0012;a2 = 0.0015;a3 = 0.0011;a4 = 0.0013;
B = zeros(4,4);
%B(3,1)=0.0002;B(3,2)=0.0003;B(3,3)=0.002;B(3,4)=0.004;
%B = [0.0002 0.0003 0.0002 0.0001;0.0004 0.0003 0.0001
%0.0002;0.0002 0.0005 0.0003 0.0002;0.0001 0.0004 0.0002 0.0002];
H = B;

%% Input differential equations
D(1) = -(u1*d(1)*d(2)/(K_x+d(1))/Y1 + u2*d(1)*d(3)/(K_x+d(1))/Y2 +
u3*d(1)*d(4)/(K_x+d(1))/Y3 + u4*d(1)*d(5)/(K_x+d(1))/Y4);
D(2) = u1*d(1)*d(2)/(K_x+d(1)) - a1*d(2)-d(2)*(B(1,1)*H(1,1)*d(6)+
B(1,2)*H(1,2)*d(7)+B(1,3)*H(1,3)*d(8)+B(1,4)*H(1,4)*d(9));
D(3) = u2*d(1)*d(3)/(K_x+d(1)) - a2*d(3)-d(3)*(B(2,1)*H(2,1)*d(6)+
B(2,2)*H(2,2)*d(7)+B(2,3)*H(2,3)*d(8)+B(2,4)*H(2,4)*d(9));
D(4) = u3*d(1)*d(4)/(K_x+d(1)) - a3*d(4)-d(4)*(B(3,1)*H(3,1)*d(6)+
B(3,2)*H(3,2)*d(7)+B(3,3)*H(3,3)*d(8)+B(3,4)*H(3,4)*d(9));
D(5) = u4*d(1)*d(5)/(K_x+d(1)) - a4*d(5)-d(5)*(B(4,1)*H(4,1)*d(6)+
B(4,2)*H(4,2)*d(7)+B(4,3)*H(4,3)*d(8)+B(4,4)*H(4,4)*d(9));
D(6) = u1*d(1)*d(2)/(K_x+d(1))/Y1;
D(7) = u2*d(1)*d(3)/(K_x+d(1))/Y2;
D(8) = u3*d(1)*d(4)/(K_x+d(1))/Y3;
D(9) = u4*d(1)*d(5)/(K_x+d(1))/Y4;
```

Appendix B Second appendix

Ecology of Fungi

Fungi, together with bacteria, are the principal decomposers in the biosphere. They break down organic materials and return the substances locked in those molecules to circulation in the ecosystem. By breaking down such substances, fungi release critical building blocks, such as carbon, nitrogen, and phosphorus, from the bodies of dead organisms and make them available to other organisms.

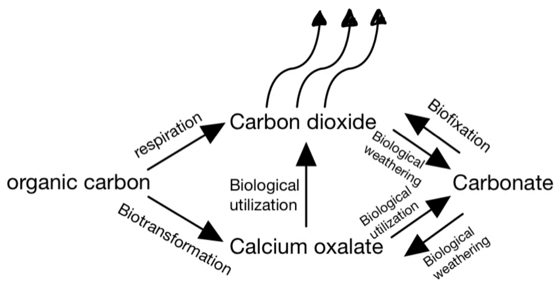


Figure 12: Carbon cycle

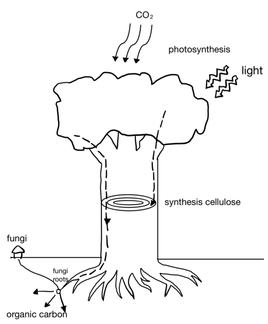


Figure 13: Fungi in carbon cycle

The threat of fungi

We really began to realize that the threat of fungi was mainly due to the following two large-scale animal deaths, both of which occurred in North America. One was the large-scale death of amphibians, and the other was the sudden large-scale infection of bats. At the same time, new fungal infections occur every year. In addition, fungi often secrete substances into the foods that they are attacking that make these foods unpalatable, carcinogenic, or poisonous.

The same aggression metabolism makes fungi ecologically important.

Mycorrhizal fungi

Mycorrhizal fungi are a type of fungi that symbiotically with plants, and they will form a mutually beneficial structure - mycorrhiza. The study found that 97 % of plants in nature have mycorrhiza.

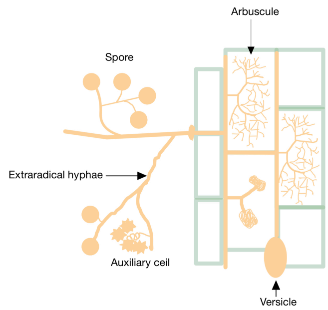


Figure 14: Mycorrhiza

Mycorrhizal fungi can promote the absorption of mineral nutrients by plants, and then promote the photosynthesis of plants. And in return, fungi get some necessary carbohydrates and other substances from plants.

Mycorrhizal fungi can promote plants to absorb mineral nutrients through three ways :

- The epiphytic hyphae of fungi are thinner, which can grow to places where the fine roots of plants cannot reach, thereby increasing the absorption of nutrients by host plants.
- Fungal hyphae have a relatively large absorption area, which can efficiently absorb water and mineral nutrients from soil and transport them to plant roots.
- Fungal hyphae activated insoluble mineral elements in soil by secreting organic

acids to make mineral nutrients more easily absorbed by host plants.

Mycorrhizal fungi can also enhance plant resistance, for example, thicken the root cortex cell wall, enhance plant defense system, inducing plants to produce antibiotics themselves etc.

Decomposition of wood fiber

Fungi are virtually the only organisms capable of breaking down lignin, one of the major constituents of wood. The decomposition of plant materials and woody fibers is an important part of the Earth ' s carbon cycle. It signif-icantly affects soil respiration and is the basis of forest soil material conversion. It plays an indispensable role in promoting material cycle, nutrient balance and maintaining the functions of forest ecosystems.

Fungi that break down lignin can be divided into white-rot fungi, Brown-rot fungi and soft-rot fungi, among which white-rot fungi have the strongest decomposition ability.

Fungi decomposition rate of woody fibers is related to many factors, the internal factors are moisture resistance, fungi growth rate, fungi density, external factors are temperature, moisture, diversity of wood fibers, etc.

Attractive prospect

- Treatment of domestic waste
  With the increasing proportion of woody fibers components in municipal solid waste, such as waste paper, waste fiber and sawdust, the composting reaction time is long, the maturity is insufficient, and the particle size of the product is large, which leads to the low economic value of the compost product and the lack of market competitiveness. Lignin - degrading microorganisms represented by white-rot fungi provide a theoretical possibility for this rapid maturity.

- Food industry
  Pretreatment of feed with lignin - decomposing bacteria can improve digestibility of animal feed.

References

[1]Peter H.Raven, George B.Johnson. BIOLOGY[M].sixth edition. Tsinghua University Press.2002 751 766

[2]Wu Kun, Zhang Shiming, Zhu Xianfeng. Research progress of lignin biodegradation[J]Journal of Henan Agricultural University 2000.12 Vol.34 No.4 349 354

[3]Lian BIn Hou Weiguo The role of fungi in terrestrial ecosystem carbon cycle [J]QUATERAEYRY SCIENCES 2011.5 vol.31 No.3 491 497