

Pioneers of the Carbon Cycle: FUNGI

Yunpeng Gao

Jiangnan University, Wuxi, Jiangsu, 214122, China

Abstract. The carbon cycle is one of the most important cycles in the Earth's ecosystem. Furthermore, fungi are a key part of the carbon cycle, and their ability to decompose organic matter such as wood and garbage can renew and utilize the carbon in organic matter. This paper combines the logistic model, the first-order kinetic equation, the GLV model and some auxiliary means to analyze the growth and reproduction of fungi. The ability to degrade organic matter is also considered. Also, we obtain the decomposition model of the fungi under the coexistence of many colonies. Firstly, we introduce the logistic model and the first-order kinetic equation (for the first-order reaction) to get the single colony degradation (SCD) model. Then, we get a relatively excellent degradation speed equation. After demonstrating its effectiveness, we extend it into the case of multiple colonies. When it comes to the condition of various colonies, we first classify the colony by Q cluster analysis, then extend the logistic model part in the SCD model to the Gause-Lotka-Volterra (GLV) model. Moreover, we get the rules of colony reproduction under the condition of multi-types fungi. It is found that under other fixed conditions, competitive types will eventually eliminate others. At the same time, we deduce the equation of the descent rate of the multi-types condition on the population quantity, and find that the decomposition ability of the multi-colony can reach the maximum when the competitive ability of each colony is relatively balanced and the degree of competition is appropriate. Then, based on the model, we find many examples of fungi and use their parameters to demonstrate that different climates lead to different species types. At the same time, by treating weather conditions as random quantities, we show that when the weather changes rapidly, there are more competitive colonies in the dry environment while the wet environment may make the low competitive colonies multiply into the largest number of colonies. When modelling, we also give the effect of biodiversity on two aspects of colony degradation, and draw the conclusion that biodiversity is usually helpful for decomposition. Finally, we analyze the sensitivity of the model, explain the influence of parameter changes on the model, and analyze the process of selecting the degradation velocity equation. At the same time, we explain the advantages and disadvantages of the model, and put forward the improvement measures and expansion schemes to make the model more reasonable.

Keywords: Logistic model; First-order kinetic equation; Q cluster analysis; GLV model; Introduction.

1. Problem Background and Model Overview

Fungi are critical in the process of breaking down and transforming organic material into forms that can be reused by other organisms, which ensures the carbon is renewed. Therefore, terrestrial fungi mediate the balance of carbon between the biosphere and atmosphere.

Furthermore, fungi are the primary decomposers of organic material in terrestrial ecosystems. There are different traits explaining fungal decomposition ability, but it is of significance to explore the relationship of two traits of interest, growth rate and moisture tolerance, and regard the decomposition rate as the primary goal.

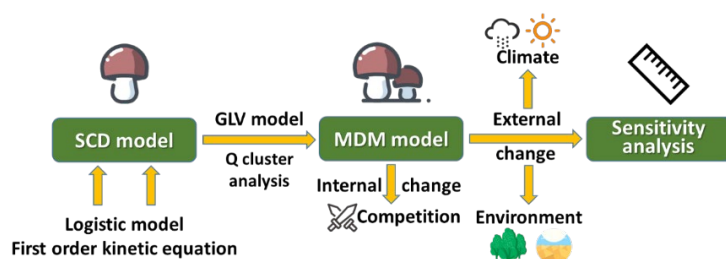


Figure 1. Model Overview

2. Preparation of the Models

2.1 Assumptions

We make some general assumptions to simplify our model.

- (a) The reaction between fungi and organic matter is the primary reaction.
- (b) The coexistence of different fungi does not affect the degradation ability of single fungi in a single colony.
- (c) Consider short-term environmental changes in a climate as changes in the degree of moisture or dryness.
- (d) Fungi in the environment can be divided into several typical categories, and there is a specific dominant colony in the specific environment.
- (e) The growth and metabolism of fungi are only affected by temperature and humidity, and moisture tolerance have a negative correlation with the degradation ability.

2.2 Notations

Here, we give all the main marks and their meanings in the paper. Any other tokens or words used as variables that appear in the paper are clearly explained in the corresponding paragraphs.

Table 1. Some notation

Symbol	Definition	Notes
N	The number of fungi in a colony or colonies.	
Q	The total amount of the degraded organic matters.	
c	The concentration of reactants.	
v	Rate.	Depending on the subscript, it can indicate the rate of chemical reaction or fungal reproduction.
α	The population growth rate in logistic model.	
β	The competition term coefficient in logistic model.	
h	The concentration of reactants produced by fungi per unit time.	
P	The probability of different weather events.	
p	Model parameter.	The effects of environmental tolerance of fungi in the model.
γ	Model parameter.	The survival competition ability of fungi with the main reactions.
d	The distance between two sample points.	

3. Analysis of Problems

3.1 Chemical Mechanism of Decomposition of Organic Matter by Fungi

One of the main subjects of this study is the relationship between the fungi degradation rate of ground litter and woody fibers and its growth rate. Therefore, we consider the biochemical processes of fungal degradation of organic matter (e.g. ground leaves, trees, etc.). Furthermore, we analyze the decomposition mechanisms to determine the key parameters affecting the process.

Lignin is a natural carbon-containing organic matter with second only to cellulose in nature, and the carbon content of lignin is as high as 60%. Through photosynthesis, plants in terrestrial ecosystem will fasten the carbon content of about 20% of the total carbon content in nature to lignin. Therefore, lignin degradation and transformation play an important role in the earth's carbon cycle. The three main monomer structures of lignin are shown in Figure 2.

Lignin degradation enzymes are mainly divided into two categories: laccase (Laccase, EC 1.10.3.2) and peroxidase. [1] To be more specific, peroxidase can also be divided into Lignin

Peroxidase (EC 1.11.1.14), Manganese Peroxidase (EC 1.11.1.13) and Versatile Peroxidase (EC 1.11.1.16) [2]. These enzymes have the potential to oxidize lignin alone. A wood rot fungus can secrete several lignin degrading enzymes at the same time [3]. The degradation of lignin by some key enzymes is taken as an example, as shown in Figure.

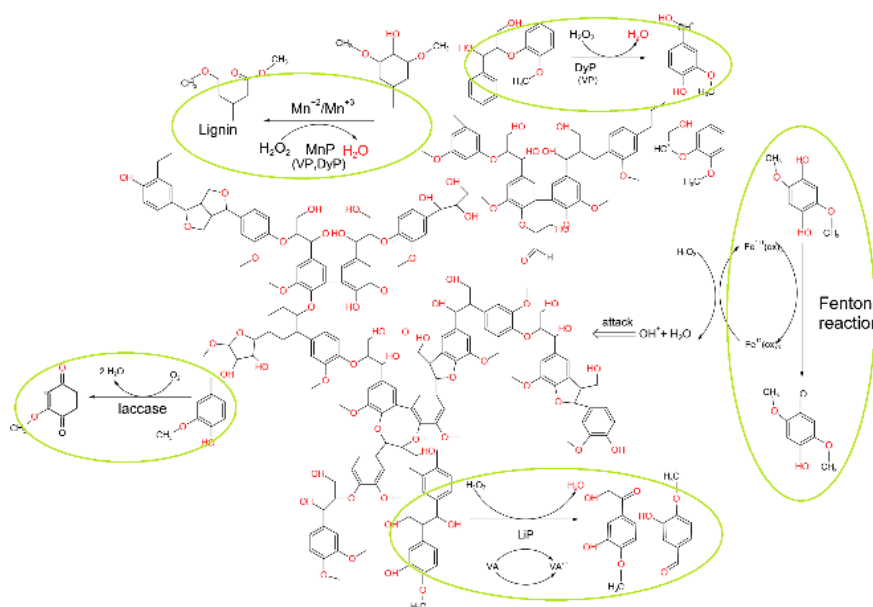


Figure 2. Three main monomer structures

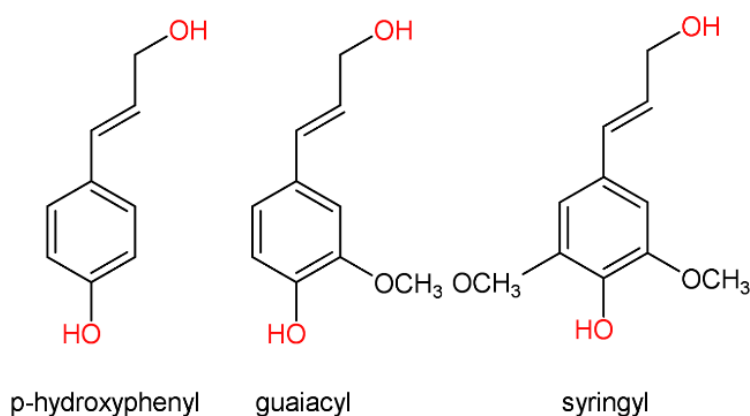


Figure 3. Enzymatic reactions [3]

Fenton reaction-mediated degradation of lignin by free radicals is the most important nonenzymatic degradation of wood by wood rot fungi element mechanism. The low molecular Fe (III) reductants can diffuse through the woods cell wall and mediate the Fenton reaction, which is the prevalent mechanism in fungi. Moreover, scientists have found that Fe (III) or other transition metals such as Cu, Mn, C and iron complexes can also react with H₂O₂ by free radicals [4]. They are deemed to react directly with lignin, whose main group is an extra cellular aromatic compound. The free radicals are the key electron carrier between enzyme and substrate, which can generate the free radical sites within the polymer, trigger cascade bond breakage, and eventually lead to lignin depolymerization.

3.2 Fungi's Characteristics

In the references given in the question, we can find two key points.

Firstly, at the individual level, decomposition ability is negatively correlated with total enzyme yield. This also shows that the decomposition rate will also increase with growth of hyphal extension rate, but the amount of increasement will slow down.

Secondly, at the coexistence of multiple colonies, the decomposition rate of fungi with great moisture tolerance is slow, while that of highly competitive fungi is rapid.

According to these two emphases, our model needs to be able to accurately reflect these characteristics and achieve a balance between the tolerance to abiotic stress and competitive advantage.

4. Single Colony Decomposition(SCD) Model

4.1 Model Construction and Analysis

It is generally believed that in a fixed patch of land, the reproduction of a single colony can be described by a logistic model [2]. Suppose N represents the number of fungi in a single colony, then N will change over time t , and we can get

$$\begin{cases} \frac{dN}{dt} = N(\alpha - \beta N) \\ N(t_0) = N_0 \end{cases},$$

where t_0 , N_0 respectively represent the initial time and initial quantity. So, it can be solved to

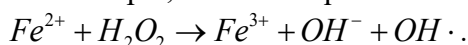
$$N(t) = \frac{\alpha N_0}{\beta N_0 + (\alpha - \beta N_0)e^{-\alpha(t-t_0)}}$$

In the previous problem analysis and expansion, we know that the main chemical reaction occurring when fungi decompose woody fibers is the Fenton reaction, which is a first-order kinetic process [3]. Meanwhile, the decomposition reactions of most substances are usually a first-order reaction. Therefore, when a single colony degrades the ground litter and woody fibers, we think that the chemical reaction that occurs can be regarded as a first-order kinetic equation to describe

$$-\frac{dc}{dt} = vc,$$

where c represents the concentration of reactants and v is the reaction rate.

When the degradation reaction occurs, the enzymes provided by fungi catalyze the degradation and accelerate the reaction rate. For example, the main equation of Fenton reaction



Wherein, fungi provide ferrous ions to make the solvent highly oxidized and then decompose organic matters.

At this point, we cannot get an accurate expression of the concentration of reactants. However, according to the reference given in the question, we can find a seemingly abnormal situation, which is that the fungi with excellent reproduction ability will have decreasing decomposition capacity. Whereas, when the fungi multiply rate increases, the growth of their decomposition rate slows up.

This seems to be reasonably explained by succession changes of community and increased competition due to lack of nutrients. Therefore, we can try to deduce the expression of reactant concentration.

Assuming that the concentration of the reactant(enzyme) in unit volume c_f is equal to $h(N)$, then bring it into the equation (3) to obtain

$$-\frac{dh(N)}{dt} = v_d h(N) \Rightarrow \frac{h'(N)dN}{dt} = v_d h(N),$$

where v_d represents the decomposition rate.

Due to $\frac{dN(t)}{dt} = v_h$, v_h is the hyphal extension rate. According to the previous logistic equation, it is easy to get

$$\begin{cases} v_d = \frac{h'(N)}{h(N)}(\alpha - \beta N)N \\ v_h = (\alpha - \beta N)N \end{cases}$$

This is the parameter equation between decomposition rate and hyphal extension rate about the N of Parameter variables. As we have already known that $\frac{d^2 v_d}{dv_h^2} < 0$, according to the Occam's Razor principle, we choose a simple and accurate expression

$$\frac{h'(N)}{h(N)} = \text{Log}(p - N),$$

where p is the relevant parameter, but also a limit on the number of N. Solving this differential equation, we obtain

$$h(N) = \frac{Ce^{-N}}{(p - N)^{p-N}}$$

where C represents arbitrary constants.

4.2 Validation of Model Effectiveness

Assuming that the number of bacteria in a single colony N_0 is 1 unit at the initial time, according to the growth rule of the fungi and the basic principle of the block growth model, the maximum capacity of the number of bacteria per unit fixed patch of land area α / β is 50 units. Since fungi can reproduce in many ways, such as budding, fission, mycelium breaking, producing asexual generation and sexual spores. They have strong reproductive ability, so the initial value colony growth rate is 1, and the coefficient of competition term is $\beta = \alpha / 50$. Since environmental parameters p positively correlated with α / β , it is assumed that $p = \alpha / \beta$ without considering other factors.

Through applying the data extension rate and decomposition rate in the references, the value of the parameter a is determined to be 1.5 [6]. It can be seen from the diagram that the growth rate obtained by the model is within a reasonable range, in line with reality, which can accurately reflect the relationship shown in Figure 4.

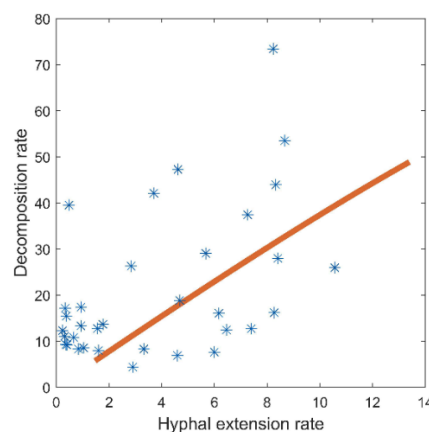


Figure 4. The relationship between the hyphal extension rate v_h and decomposition rate v_d

After determining the parameters, plot N , $h(N)$, v_h , v_d with time t , which can be reflected in the Figure 5. Using the above model, the reproduction and decomposition process of a single colony can be simplified and simulated. Intuitively, the growth process can be divided into the delayed period I of adapting to new environment, the exponential period II of rapid balanced growth, the stable period III of peak extension and decomposition rate, and the decline period IV of a large number of bacterial deaths. Over time, the number of Fungi N is growing continuously. As $t = 9$, the model is stable with no change in indicators which indicates the system is balanced. In the early days, the growth rate of fungi and the amount of enzymes

secreted increase slowly. Because at this stage, the fungi is in the delayed phase where cells mainly synthesize ribosomes, ATP and so on to promote morphology. It is beneficial for the metabolic system to adapt to the new environment. Then fungi getting into the index period, in a suitable environment with adequate nutrients, cells start to grow rapidly and stably with active enzymes and vigorous metabolism. When the number of newly bred cells is equal to the number of dying cells, in a brief period of stability, extension rate and decomposition rate peak.

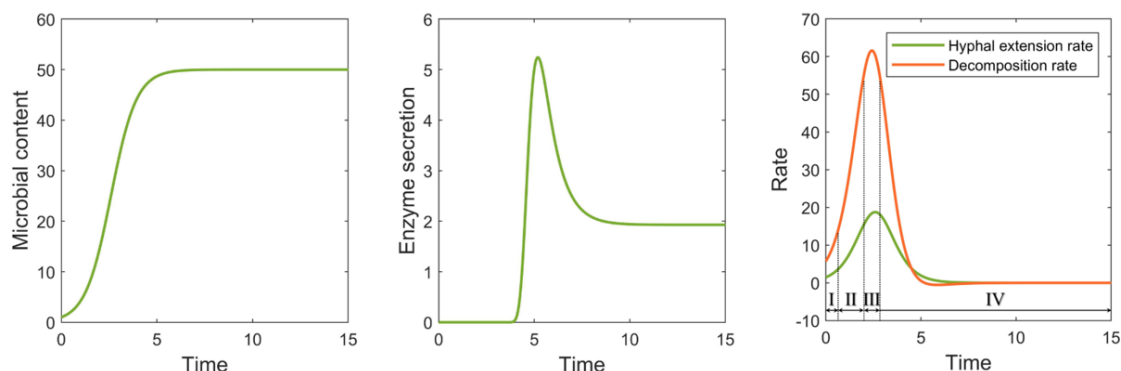


Figure 5. Growth and degradation of single colonies

Because the environment is more unfavorable gradually to growth and the fungi get into the decline phase, the cell catabolism obviously exceeds the anabolism and leads to the death of a large number of bacteria. However, at this time, it still has the ability to synthesize and secrete the target enzyme. Therefore, the secretion of enzymes reaches its maximum at the end of this period. Finally, due to cell cleavage and other factors which lead to the original secreted enzyme being partially destroyed, the amount of enzyme was reduced to a balanced value to continue to catalyze the degradation reaction, which is shown in Figure 6 where $h(N)/N$ is the amount of enzyme produced by the number of bacteria.

By plotting the time t , we can see that the trend of $h(N)/N$ and h is roughly the same. When the extension rate increases, the growth rate slows down. When the $h(N)/N$ reaches the peak value and then decreases to an equilibrium value, it meets the conditions given in the title.

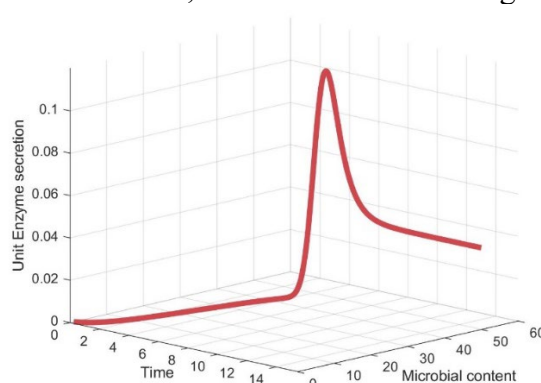


Figure 6. The relationship between the microbial content N and unit enzyme secretion $h(N)/N$

5. Multicolony Decomposition Model(MDM)

5.1 Model Construction and Analysis

Corrosion mechanism of different colonies on woody fibre is not exactly the same, but the difference is very tiny. According to the hypothesis, we think that the coexistence of multiple enzymes caused by the coexistence of multiple colonies does not affect the chemical reaction catalyzed by individual enzyme. Then we only consider the effect of the coexistence of multiple colonies on the reproduction of a single colony. Under the single colony decomposition (SCD) model in Section 4, the logistic model is affected by the reproduction system, in which the main influencing parameters are the growth rate a with the coefficient of competition term β .

When it comes to fungi, we have numerous lefts to catalogue. Currently, 148,000 species have been identified, primarily in the Ascomycota and Basidiomycota phyla. But scientists believe that more than 90% of species remain unknown to science. They estimate that there are from 2.2 to 3.8 million species on Earth. The specific data are shown in the Figure 8(a). Whereas almost all plants are visible above ground, fungi often remain concealed. Its main habitat is shown in Figure 8(b).



Figure 7. (a) The proportion of species from each continent named as new to science in 2019 [5] (The relative size of the continents reflects the number of species named from each.); (b) Ecology (occurrence) of lignin-degrading fungi [2].

Because symbiotic colonies are often diverse and varied, we need to consider colonies with similar growth ability as the same kind. Assuming that the population growth rate of the colony i is α_i and the competition term coefficient is β_i , then the vector $\mathbf{x}_i$ is equal to (α_i, β_i) . So $\mathbf{x}_i$ can be seen as one of the points in $\mathbb{R}^2$, namely the sample point of a colony. Due to different dimensions between α_i and β_i , we use Mahalanobis Distance to describe the distance of two sample points as d , that is

$$d(\mathbf{x}_i, \mathbf{x}_j) = \sqrt{(\mathbf{x}_i - \mathbf{x}_j)^T \Gamma^{-1} (\mathbf{x}_i - \mathbf{x}_j)}$$

where $\mathbf{x}_i, \mathbf{x}_j$ is a sample of a population Z from observations, and Γ is the Z covariance matrix, which is estimated with Z sample covariance. At this time, Q cluster analysis can be used to divide the colony into a few categories, and the degradation of the material in each category can be estimated as a whole.

At this point, based on a small number of categories, we use an improved logistic model, Gause-Lotka-Volterra (GLV) model, to simulate fungal changes. The number of fungi that a particular fungi i contains in a population of fungi n is $N_i (i = 1, 2, \dots, n)$, then we have

$$\begin{cases} \frac{dN_i}{dt} = N_i \left(\alpha_i - \beta_i N_i - \sum_{k \neq i} \gamma_k N_k \right) \\ N_i(t_0) = N_{i0} \end{cases}$$

Where γ_k represents the competitive ability of colony k. The more competitive the colony is, the stronger its inhibition of the reproduction of other communities will be, then γ_k will increase. At the same time, as pointed out above, when the colony is more competitive, the environmental tolerance is also stronger, and relative degradation ability is poorer. So γ_k is negatively correlated with the p in the model. To be clear, at $n > 2$, this ordinary differential equation group has no analytical solution, but it is easy to obtain its numerical solution after determining the values of each parameter. According to the previous analysis, the degradation rate v_{id} and reproduction rate v_{ih} of each colony will meet the equation

$$\begin{cases} v_{ih} = N_i \left(\alpha_i - \beta_i N_i - \sum_{k \neq i} \gamma_k N_k \right) \\ v_{id} = \text{Log}(p - N_i) v_{ih} \end{cases}$$

At the same time, the overall degradation rate is the equation $v_d = \sum_{i=1}^n v_{id}$.

5.2 The Analysis in System Internal Change

Since we have classified colonies in advance in our model, the number of equations in differential equations is not large, and the parameters of each category must be different. Then in these categories, there must be a fungus with the strongest competitiveness. According to the GLV model in Section 5.1, it is foreseeable that in the short term, there are many kinds of fungi, but in the long run, the species of fungi will gradually shrink to the only one with the strongest competitiveness.

Under this background, we study the degradation of organic matter by fungi in the short and long term. Considering the fungal population containing three fungal classes, the total amount of organic matter degraded Q at time t is equal to

$$\begin{aligned} \int_0^t v_d dt &= \int_0^t \sum_{i=1}^3 v_{id} dt \\ &= \sum_{i=1}^3 \int_0^t \text{Log}(p_i - N_i) N_i \left(\alpha_i - \beta_i N_i - \sum_{\substack{k \neq i \\ 1 \leq k \leq 3}} \gamma_k N_k \right) dt \end{aligned}$$

As noted earlier, there is a negative correlation between Y_k and p, so we further simplify the expression to

$$Q(t) = \sum_{i=1}^3 \int_0^t \text{Log}(A - B\gamma_i - N_i) N_i \left(\alpha_i - \beta_i N_i - \sum_{\substack{k \neq i \\ 1 \leq k \leq 3}} \gamma_k N_k \right) dt,$$

Where A, B of it are related parameters.

First of all, because of the negative correlation between competitiveness and degradation ability, we can naturally conclude that when all colonies in colony population have strong competitiveness, the growth of Q will be very slow, whereas the growth of Q will be relatively rapid. However, when the competition ability of different colonies is different, it needs specific analysis.

Suppose that colony class 1 has the strongest survival competitiveness, then by changing Y1, we numerically integrate by software MATLAB and get the curve of Q over time as shown in Figure 9.

We can intuitively see that when the degradation level is relatively large, the degradation level will be relatively small. However, a special example is that when Y1 is extremely small, that is, the

survival competitiveness of the three colonies is similar. At this point, in the short term, the bacterial community degradation capacity is very strong, far ahead of other

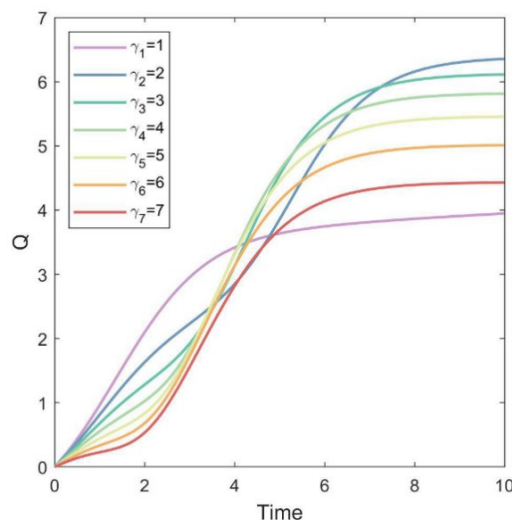


Figure 8. The effects of competition ability of community type 1 on Q

situations. Nevertheless, in the long run, colony degradation is the worst. This is because the competitiveness of the colony is similar, the competition will be very fierce, resulting in the stable number of community groups and poor natural degradation ability. Second, we find that when γ_1 is slightly larger than this situation, that is $\gamma_1 = 2$, the final amount of organic matter degradation is the most. This shows that the community population maintaining moderate competition, neither too fierce, nor too weak to let a group of species take too much advantage, can achieve the best degradation effect.

The fact is that if you get more value, take $t = 10$ as the Q standard, as shown in Figure 10. It can be found that the maximum value is obtained between 1 and 2, that is to say that the degradation effect is the best.

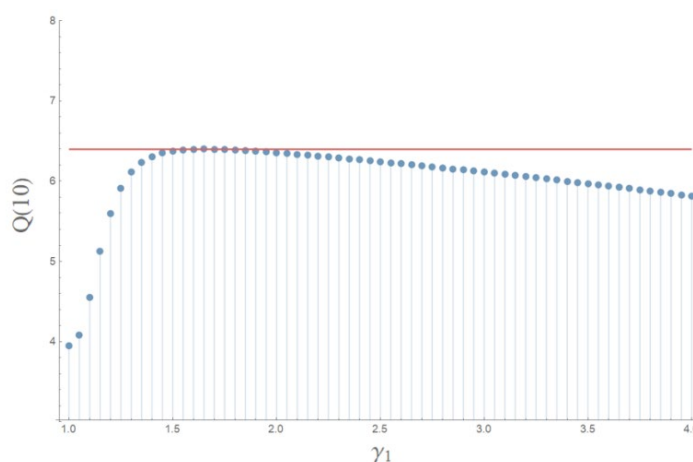


Figure 9. The effect of γ_1 change on Q (10)

At the same time, it is worth noting that in the short and long term, the gap between Q in different situations is obvious. But in transition, there will be a period when the gap of Q between different situations is very small. This means that the degradation rate of different conditions is different in the short term, but the degradation effect can often be small. Only after a long time will there be obvious differences in the degradation effect.

The situation is similar when more than three colonies are in the colony group. After classification, there must be a colony with the strongest competitiveness. When the colony has strong

competitiveness, the degradation effect of the colony will be poor. Otherwise, the degradation effect will be excellent. When the competition of multiple colonies is too fierce, the long-term degradation effect will be poor, and when the competitiveness of one colony is obviously stronger than that of other communities, the short-term degradation effect will be bad. Only by maintaining moderate competition can the long- and short-term degradation effect be outstanding.

At the same time, from two aspects, we can analyze how the diversity of fungal communities of a system impacts the overall efficiency of a system with respect to the breakdown of ground litter.

6. Sensitivity Analysis of the Model

6.1 Sensitivity Analysis of Single Colony Decomposition Model

The parameter a and 0 are obtained by fitting the relationship between hyphal extension rate and decomposition rate of different bacteria in the single colony model, so that the model can reflect well the growth and decomposition of single colony of common fungi. To understand the influence of a and 0 on the model more accurately, we conduct the sensitivity analysis. That is say that to control other conditions, change the value of parameter a and 0 to the original 90%, 95%, 105%, 110%, and map the hyphal extension rate and decomposition rate to observe the changes of the two.

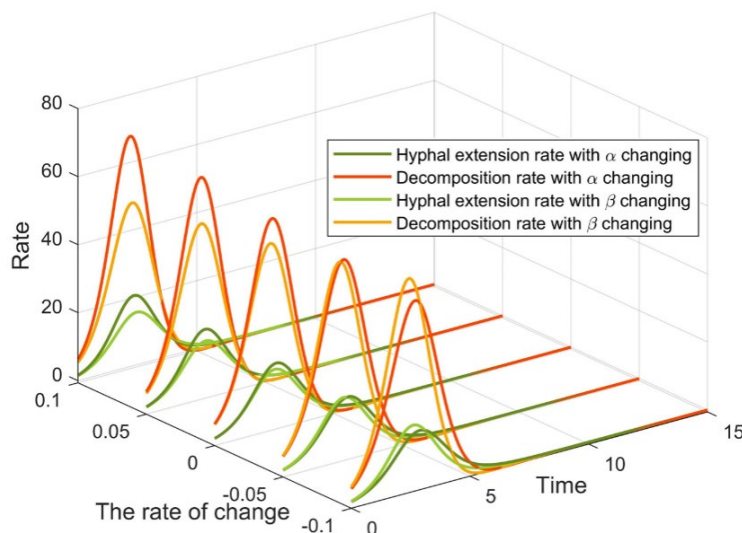


Figure 10. Sensitivity analysis of single colony model

As can be seen from Figure 10, hyphal extension rate and decomposition rate are positively correlated with a and negatively correlated with 0 . If the parameters change to the same degree, the speed is more sensitive to the a and the range of change is greater. Overall, because the a or 0 changes, the two rates do not fluctuate sharply, and almost change in the same proportion, so it is still in line with the growth of fungal colonies in real life, indicating that the model has a certain robustness.

6.2 The Selection Analysis of $h(N)/h(N)$

We have verified the validity of regarding $h'(N)/h(N)$ as $\text{Log}(p-N)$ in Section 4.2. Here, we analyze what happens when $h'(N)/h(N)$ takes some other functions.

From the most classical power function, if you take

$$\frac{h'(N)}{h(N)} = (p-N)^\mu,$$

Then it's easy to solve

$$h(N) = Ce^{\frac{(p-N)^{1+\mu}}{1+\mu}}.$$

The function value shows exponential growth, which is inconsistent with objective facts. In fact, since $h(N)$ is greater than 0, if $h'(N)/h(N)$ is also greater than 0, then $h(N)$ is bound to be greater than 0, resulting in a continuous increase in $h(N)$, respectively. And we know that the degrading enzyme produced by the colony must return to 0 in the end, so $h'(N)/h(N)$ needs to change from positive to negative. It is not difficult to find out that $\text{Log}(p-N)$ can perfectly meet all the needs, but also a very simple form of elementary function, including the most common natural logarithm in nature, which is the best choice.

6.3 Sensitivity Analysis of Multicolony Decomposition Model

In the multi-colony model, we focus on the population competition within the system and the impact of the external environmental changes on the model, in which the environmental impact has been analyzed thoroughly in Section 5.3, and it will not be restated here. However, for the internal effects, only the change of parameter γ representing competitiveness is considered. Because the growth of colonies is closely related to its degradation ability, it is of great significance to further understand the influence of internal reasons on the growth of fungi. To change the α , β and N_0 of the three fungi mentioned in Section 5.2, we find that the effect of α and β is similar to that of single colony model, so the influence of N_0 is analyzed emphatically.

With the competition ability $\gamma_1 = \gamma_2 < \gamma_3$, initial bacteria quantity $N_{01} = N_{03} < N_{02}$ of three types of fungi, change the initial bacteria quantity of three types in turn, make it change in the range of 90%-110% of the initial value, the result is shown in Figure 11.

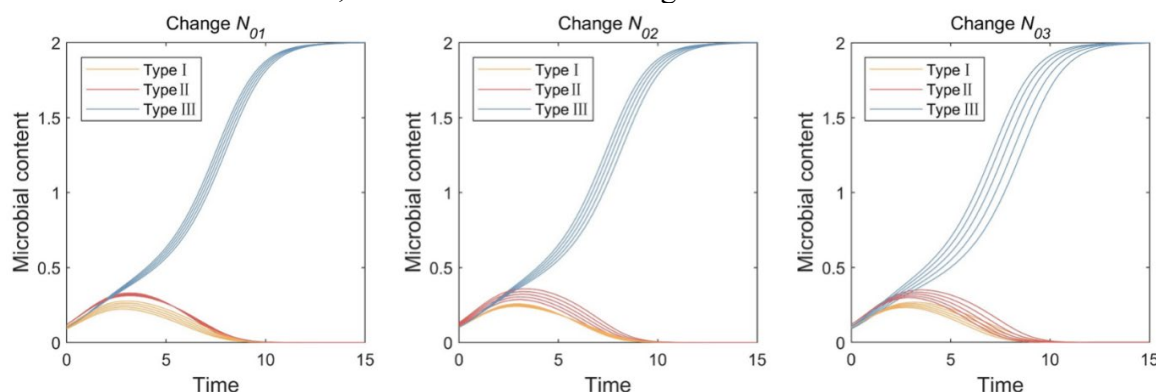


Figure 11. The Analysis of Sensitivity of Polycolony Model to N_0

7. Conclusions

This paper combines the logistic model, the first order kinetic equation and the GLV model and some auxiliary means to analyze the growth and reproduction of fungi and the ability to degrade organic matter, and then obtains the degradation model of fungi under the coexistence of many colonies.

In the single colony degradation (SCD) model, we verify that the temperature and moisture resistance are positively correlated and negatively correlated with the decomposition ability of the single colony. After that, we derive a multi-types degradation model based on the GLV model. When the survival competitiveness of the colony is similar, the degradation ability of the community is far ahead of other situations in the short term, but in the long run, the degradation ability of colony group is the worst. Because fierce competition limits the number of colony group and natural degradation ability. However, when the competition ability of different colonies is large, the moderate competition between communities is neither too fierce nor too weak in order to achieve the best degradation effect.

Then, on the basis of this model, we demonstrate that different types of dominant bacteria will be produced according to environmental characteristics in different climates. When weather changes rapidly, there will be more highly competitive colony reproduction in dry climate. However, the wet environment may allow low-competitive colonies to multiply into the largest number of colonies. Since the global weather is unpredictable, a single dominant type is easy to lose its advantage or even die in the process of weather change. At the same time, moderate population competition is beneficial to the improvement of degradation effect. Besides, the diversity of fungal communities will narrow the gap between the most competitive colony and the less competitive colony, on the other hand, it will affect the initial population value of different colony groups and thus impacts the overall efficiency of a system with respect to the breakdown of ground litter.

Finally, through the sensitivity analysis of the model, we find that the parameters do not affect the overall trend of the model after a certain degree of change, and verify the robustness of the model.

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