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ARTICLE

Establishment of Fungal Decomposition Model Based on OLS and Logistic Model

Mingkai Zhou Bingjie Sun Wentao Wu*

North University of China, Taiyuan, Shanxi, 030051, China

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ABSTRACT

By using the OLS model, an equation for the rate of decomposing wood by a variety of fungi was established. We analyzed the effects of various fungi in the experimental data under different temperature and humidity. Based on the growth performance of different fungi at different temperatures and humidity, we use the method of systematic cluster to divide the fungi into 5 categories, and introduce competition levels as the viability of different species of fungi. We have established a logistic model that introduces competition levels to obtain a fungal habitat model. The fungal habitat model includes predictions about the relative advantages and disadvantages for each species and combinations of species likely to persist, and do so for different environments including arid, semi-arid, temperate, arboreal, and tropical rain forests.

1. Introduction

1.1 Problem Background

Fungi account for 81-95% of soil microbial biomass [1], which play a key role in the plant-soil-atmosphere carbon cycle, but unfortunately have not received much attention. Undoubtedly, the study of the role of fungi in the carbon cycle of terrestrial ecosystems is of great significance to our understanding of the mechanisms by which organisms regulate the global carbon cycle. A key component of the carbon cycle is the decomposition of plants and wood fibers, so it is necessary to study the role of fungi in the decomposition of wood fibers and the fungal traits that determine the rate of decomposition during the process. A recent article about fungi decompose lumber [2], in the laboratory, analysis of 34 kinds of rot fungi, from North America and in combination with a 5 years of field research, the research which properties can affect the fungal decomposition rate, come to a conclusion: the effect of fungal growth rate for wood decomposition rate effect is strongest, and to individuals, decomposition rate, and negatively correlated with wet resistance. Below are pictures of the fungus we used in our paper:

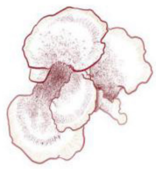
1.2 Restatement of the Problem

Considering the background information and restricted conditions identified in the problem statement, we need to solve the following problems:

**Corresponding Author:*
Wentao Wu,
North University of China, Taiyuan, Shanxi, 030051, China;
Email: 2396352599@qq.com



(a)f_fom (b)p_har (c)a_gal

(d)p_robin (e)p_sang

Figure 1. Pictures of fungi

(To avoid copyright infringement, we draw and generate Figure 1 on our own)

- In general, a mathematical model is set up, to describe fungal activity effects on litter and wood fiber.
- Further thinking about how to represent in the model and growth rate and how to make different fungi during the merger process.
- We need to build model is: under the same initial conditions, what will happen between different types of fungal evolution of types of community. The short - term and long - term trends of the interaction are obtained. And to study whether small changes in initial conditions will affect the different trends of subsequent community evolution. For example, a fungus goes from being an advantage to a disadvantage. It is further considered to add initial environmental factors into the model to further assist the influence of local weather pattern changes on the model.
- Using model for each species or could continue for a period of time the combination of comparative advantage, disadvantage, and in different circumstances.
- The model is used to analyze the influence of the number of fungi species on the overall efficiency of the ground waste classification system, and to analyze and predict the influence of biodiversity when the environment changes to different degrees.

2. Assumptions and Justifications

- We assume that environmental resources are limited, and there is only competition between different species, and there is no other relationship.
- Fungal growth is affected by a variety of variables [4], but we only take into account temperature and humidity and the moisture tolerance, growth rate and decomposition rate of the fungus itself, The influence of other factors on the growth of fungi, such as pH, oxygen concentration, carbon dioxide concentration, REDOX potential, and the utilization of required substances, were not considered.
- When we think about environmental change, we only think about temperature and humidity, As we know from the literature given by the title: temperature has a strong correlation with the decomposition rate, and the fungus growth rate has the strongest effect on the decomposition rate of wood, and the moisture resistance also has a strong negative correlation with the decomposition rate [5].

3. Method

3.1 Notations

The key mathematical notations used in this paper are listed in Table 1.

Table 1. Notations used in this paper

Variable	Description	Unit
σ_i	The competitive factor of the ith fungus	-
$x_i(t)$	The initial number of fungus at time t	-
$x_i(0)$	The number of the ith fungus at t = 0	-
N_i	The maximum number of species I in the initial environment	-
r_i	The growth rate of species I	-
r_{i0}	The growth rate of the ith species at the initial moment	-
AI	de Martonne Dry index	-
P	Mean precipitation	mm
T	The average temperature	℃
α	Competitive factors after introducing environmental variables	-
Y	Mass loss over 122 days (% dry weight), geometric mean across 10,16, and 22 °C	
x_1	Linear extension rate	(mm day-1)
Hyphal density	Dry mass (μg cm-2) at 1 cm from the edge of the growing front	

3.2 Wood Decomposition Rate Model

Given the decomposition of wood [7] is a key factor in a variety of fungal activity, it can be judged that there is a mathematical relationship between the growth of fungi and the rate of wood decomposition. In this model, we limit the focus to the discussion: in the presence of a variety of fungi, to study the factors affecting the rate of wood decomposition.

3.2.1 Establishment of Wood Decomposition Rate Model

According to Nicky Lustenhouwer's research [2], the main factors affecting the decomposition rate of fungi

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are the growth rate and moisture resistance. And different kinds of fungi also have different decomposition rates. Based on these three factors of fungal decomposition. We use multiple linear regression (OLS) to build a model without considering environmental factors. We use this equation to describe the quantitative relationship between fungal decomposition rate and other variables。 We first standardize the data to remove the impact of different dimensions。 Building the following OLS model [8]:

$$\begin{cases} y_1 = \beta_0 + \beta_1 x_{11} + \beta_2 x_{12} + \cdots + \beta_p x_{1p} \\ y_2 = \beta_0 + \beta_1 x_{21} + \beta_2 x_{22} + \cdots + \beta_p x_{2p} \\ \vdots \\ y_n = \beta_0 + \beta_1 x_{n1} + \beta_2 x_{n2} + \cdots + \beta_p x_{np} \end{cases}$$

In this model ,y_n represents the decomposition rate [16] of the fungus, The independent variable X_{nn} is the factor that affects the rate of fungal decomposition.X_{n1} represents growth rate. X_{n2} represents Moisture resistance. X_{n3} to X_{nn} represents fungus species (Fungus species as a qualitative variable, using dummy variables to describe). And β is the coefficient of multiple linear regression.

3.2.2 Solution of Wood Decomposition Rate Model

Regression using 20 sets (x_{1i}, x_{2i} ,x_{3i}……$x_{20i)}$ of observations. The table is part of the data obtained by regression:

Table 2. OLS results

	β_1	β_2	β_3	β_4
result	0.77	-0.34	0.05	0

The equation obtained through OLS regression can describe the relationship between each independent variable and the dependent variable. In the same environment and without considering interaction, analyzing the regression results, we can get that the decomposition rate of most bacteria is not much different. The coefficient value before the dummy variable is relatively small, indicating that the type of bacteria has a limited influence on the decomposition rate. The growth rate of the bacteria has a greater impact on the decomposition rate of the bacteria, and the coefficient before the variable is 0.77. Indicates that the faster the bacteria grow, the faster the decomposition rate. The humidity has a negative correlation with the decomposition rate.

3.2.3 Checking of Model Wood Decomposition Rate Model

Since the data are cross-sectional data, heteroscedasticity may occur. Compared with BP test, the White test can test various forms of heteroscedasticity. Therefore, we perform

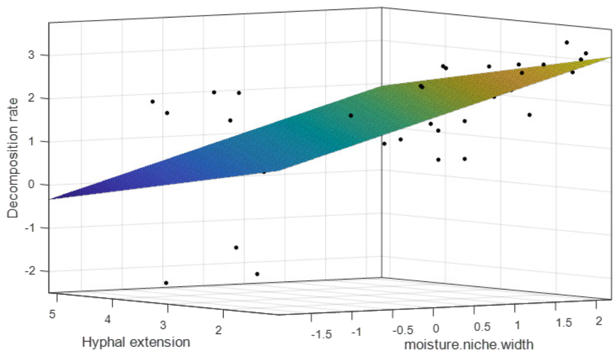

Figure 2. Simplified multivariate equation image

Table 3. White test

	Chi2(151)	Probin>chi2
result	28	0.4658

White's test on the multivariate linear equation to check whether the equation has heteroscedasticity. White test results are as follows:

The P value is greater than 0.05, and the null hypothesis is rejected at the 95% confidence level. We believe that the disturbance term has no heteroscedasticity. Then check the multicollinearity of the equation, see the appendix for the results. Its mean VIF is 8.91, which is less than 10. Therefore, we believe that there is no multicollinearity in the equation.

3.3 Clustering and Growth Competition Model

3.3.1 Fungi Cluster Model

Establishment of Fungi Cluster Model

We used systematic cluster analysis to classify the fungi in the data. We take the optimum temperature and humidity for the fungus to survive as indicators [13]. And standardized it before the algorithm to eliminate unreasonable clustering results caused by large dimensional differences.

$$d\left(\vec{x_i}, \vec{x_j}\right) = \sqrt{\sum_{i=1}^{p} \left(x_{ik} - x_{jk}\right)^2}$$

Combine the two data points that are closest to each other, and iterate over and over again. We do this until we put all the data points together. Finally, the cluster spectra are generated and the results are obtained.

Solution of The Establishment of Fungi Cluster Model

We can use Elbow Method when we choose the final category total, Here's how it works: assume a value, That is, assume the largest possible number of class clusters, and then increase the number of class clusters from 1 to i. After calculating, we get i value of SSE, Based on the underlying pattern of the data, When the set number of

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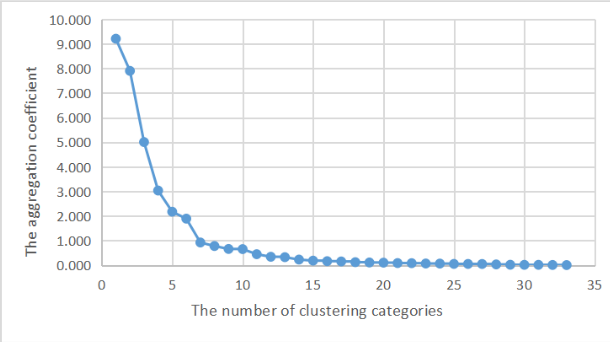

Figure 3. pedigree diagram

class clusters keeps approaching the real number of class clusters, When the set number of class clusters keeps approaching the real number of class clusters SSE, It shows a trend of rapid decline. When the set number of class clusters exceeds the real number of class clusters, SSE will go down. But there is no rapid decline, So by looking for an inflection point in the SSE minus K curve, you can effectively find the value of K.

According to the Polymerization coefficient line chart, We can draw the conclusion:When K changes from 0 to 5, the distortion degree changes the most. When K exceeds 5, the variation of distortion degree decreases significantly, and the downward trend of broken lines gradually slows down. We can set the number of categories as 5.

Figure 4 shows the clustering results, and there are 5 types of copolymerization. The list is as follows:

Table 4. Compete for league tables

Fungal species	Group 1 fungi	Group 2 fungi	Group 3 fungi	Group 4 fungi	Group 5 fungi
Optimal temperature	normal	high	high	low	high
Optimum humidity	dry	semi-arid	wet	semi-arid	semi-arid

3.3.2 Logistic-Based Fungal Growth Competition Model

Establishment of Logistic-Based Fungal Growth Competition Model

We define σ_i as the competitive factor for the ith fungus, $x_i(t)$ is the initial number of the ith fungus at time t, $x_i(0)$ is the number of the ith species at time t=0,N_i is the maximum number of the ith species in the initial environment, r_i is the growth rate of species I, r_{i0} is the growth rate

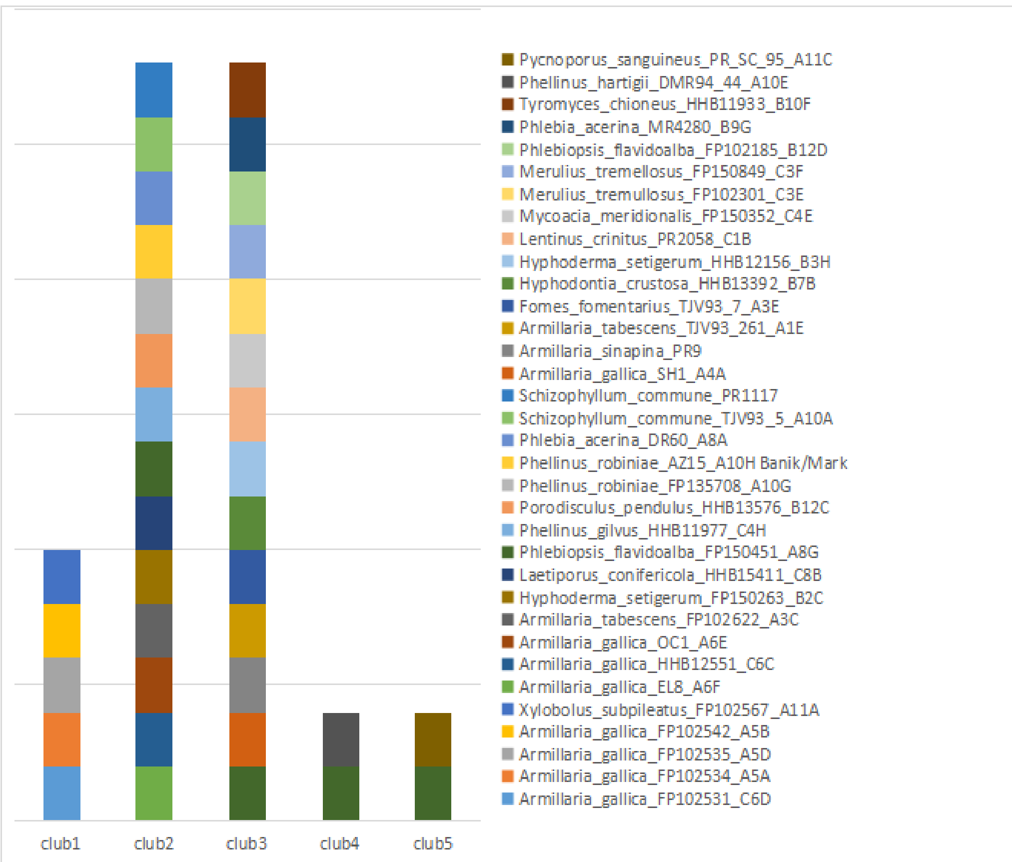

Figure 4. Cluster analysis result diagram

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of the ith species at the initial moment.

We further assume that environmental resources are finite, The relationship between I species of fungi is competitive relationship, The initial numbers of different fungi were equal and the maximum number of different fungi in the initial environment was the same, Assume that the growth rate of the ith fungus is 0 under the initial environment.

Consider two species competing with each other as they survive with limited natural resources (let's consider the first and second fungi first).If the effect of the second fungus is not considered, the population change of the first fungus obeys that:

$$\frac{dx_1(t)}{dt}=r_1x_1\left(1-\frac{x_1}{N_1}\right)$$

Where, the factor that $1-x_1/N_1$ reflects the retarding effect of the first fungus on its own growth due to the consumption of limited resources. If we add to that the competing effects of a second fungus, It means that the second fungus's consumption of food affects the growth of the first fungus, So we change the factor to this:

$$1-\frac{x_1}{N_1}-\sigma_1\frac{x_2}{N_2}$$

So this is the conclusion of the first fungus:

$$\frac{dx_1(t)}{dt}=r_1x_1\left(1-\frac{x_1}{N_1}-\sigma_1\frac{x_2}{N_2}\right)$$

Similarly, this is the conclusion of the second fungus:

$$\frac{dx_2(t)}{dt}=r_1x_1\left(1-\frac{x_2}{N_2}-\sigma_2\frac{x_1}{N_1}\right)$$

When n species of fungi survive under the condition of limited natural environmental resources, they compete with each other, For 1~ N species of fungi, there are the following formulas:

$$\begin{cases}\dfrac{dx_1(t)}{dt}=r_1x_1\left(1-\dfrac{x_1}{N_1}-\dfrac{\sigma_1}{N}\displaystyle\sum_{i=2}^{n}x_i\right)\\ \vdots\\ \vdots\\ \vdots\\ \vdots\\ \dfrac{dx_n(t)}{dt}=r_nx_n\left(1-\dfrac{x_n}{N_n}-\dfrac{\sigma_n}{N}\displaystyle\sum_{i=2}^{n}x_i\right)\end{cases}$$

Solution of Logistic-Based Fungal Growth Competition Model

In the previous paper we divided 34 fungi into five groups, namely n=1,2,3,4,5, but we will consider only the first group of five fungi here. So we get the results of the growth of five fungi in the same environment:

Through Figure 5, there is little difference in their optimal temperature, but there are differences when they grow in the same environment. This also supports our hypothesis that there is competition between the fungi.

The reason there are only three curves in the figure is: The three types of fungi, a.gal1.s, a.gal2.s, a.gal3.s, compete in the same ranking, so the competitiveness is almost the same. It causes the curves to overlap. We further conclude that: At the same temperature and humidity, these three fungi are at a disadvantage. Their numbers are slowly declining and could be zero in the future. The most dominant fungus, A. Sub. S, is increasing in number. When t=15h, the increasing trend of quantity tends to be stable. The fifth fungus, A. gal5.s, has a slight edge over

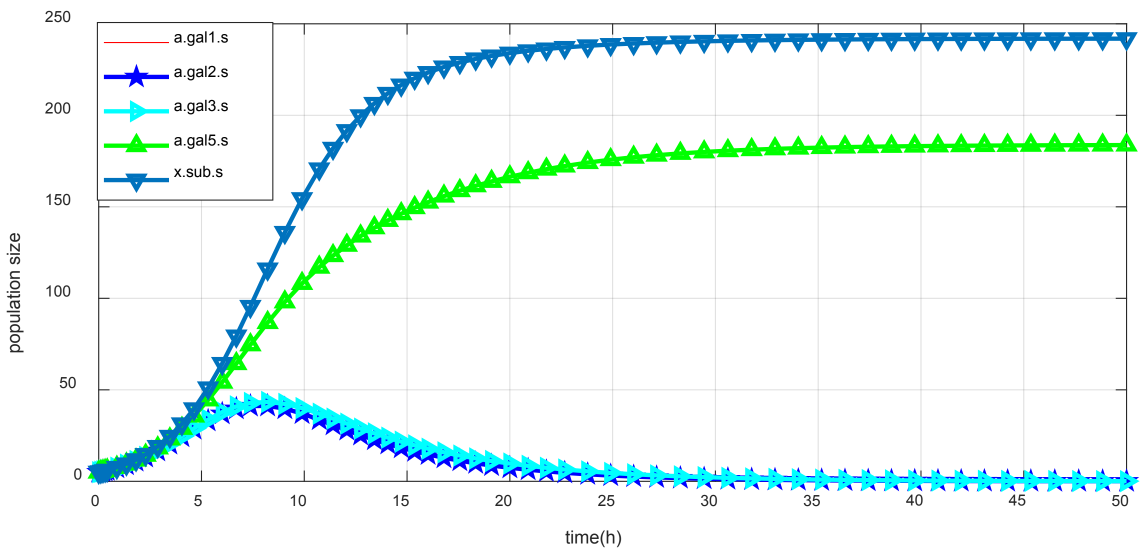


Figure 5. Five kinds of fungi competition simulation diagram

the competition and is slowly increasing in number. When t=20, the increase trend of its number tends to be stable. The following table shows the competitive ranking[12] of the five fungi studied:

Table 5. Compete for league tables

Name	a.gal1.s	a.gal2.s	a.gal3.s	a.gal5.s	a.sub.s
Competitive ranking	0.054	0.054	0.054	0.135	0.243

3.4 Improved Logistic Model of Fungal Growth

3.4.1 Establishment of Improved Logistic Model of Fungal Growth

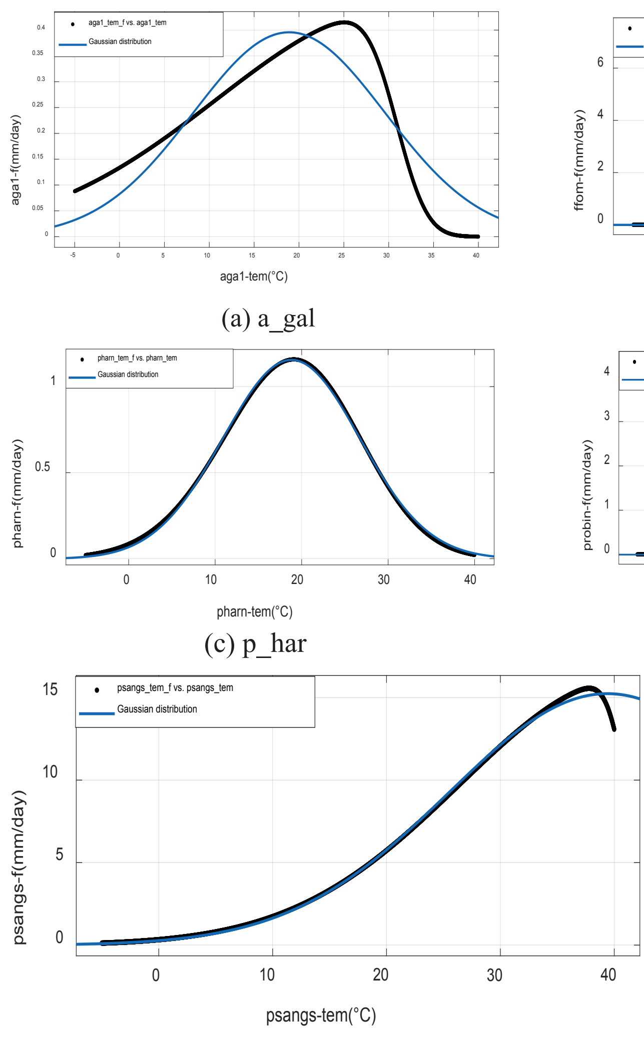
To solve the problem that the influence of small changes in initial conditions on the evolutionary trend of the community, We consider adding initial environmental variables [18] to the model to solve this problem. Since fungi are divided into 5 categories above, we can select a fungus from each category for study. We fit the Fungi data includes optimum humidity and optimum temperature for growth. It is calculated that temperature T and humidity M obey Normal distribution, namely:

$$f(x) = a_1 \cdot e^{\left[-\left(\frac{x-b_1}{c_1}\right)^2\right]}$$

We get the fitting curve, the first five pictures are the fitting curves of temperature and growth rate. The last five pictures are the fitting curves of humidity and growth rate.

Table 6. Table of fitting curve SSE and R^2 values (The temperature)

	aga1	ffom	pharm	probin	psangs
SSE	14.306	18.9621	0.7615	16.0814	11.1826
R^2	0.8162	0.9427	0.9989	0.9047	0.9983



(a) a_gal (b) f_fom (c) p_har (d) p_robin (e) p_sangs

Figure 6. The fitting curves of temperature and growth rate

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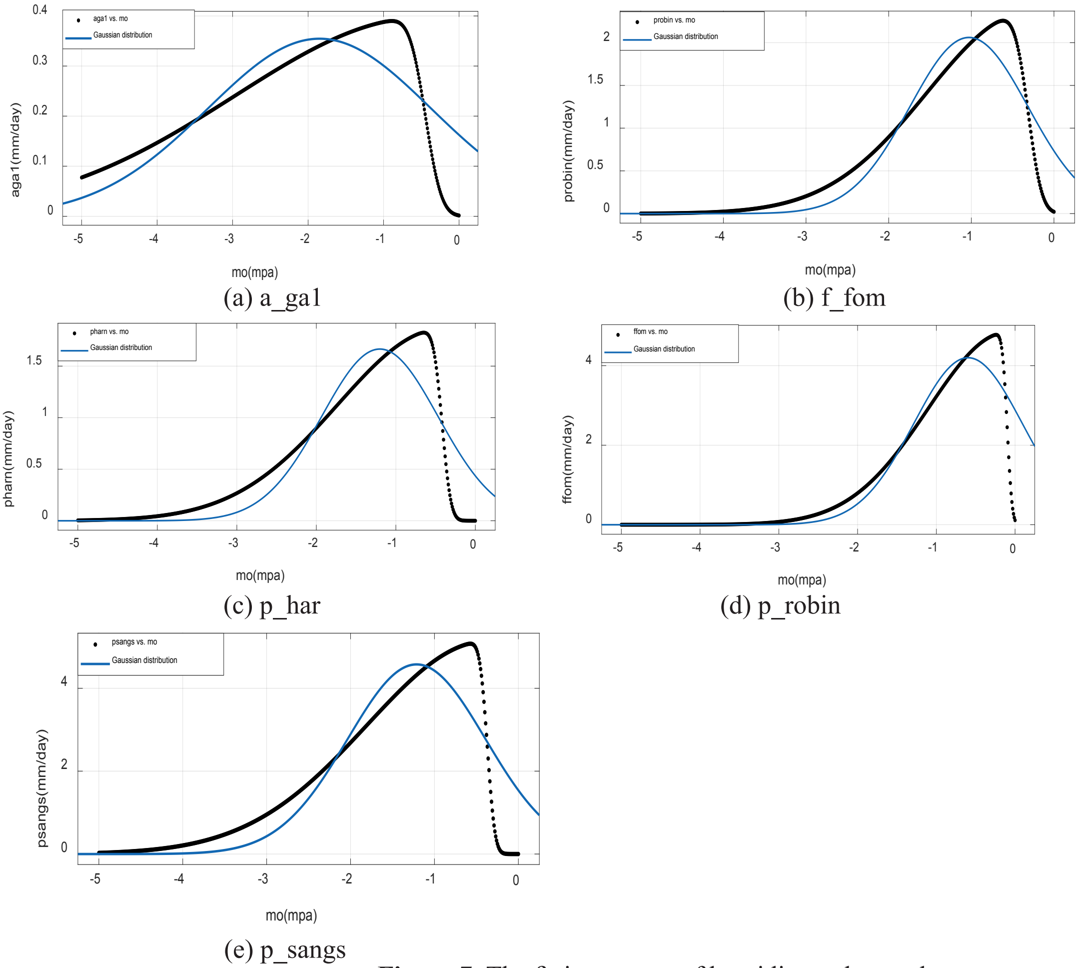


Figure 7. The fitting curves of humidity and growth rate

Table 7. Table of fitting curve SSE and R^2 values (The humidity)

	aga1	ffom	pharm	probin	psangs
SSE	3.4811	8.3632	4.6713	4.6121	0.2508
R^2	0.8026	0.9053	0.9317	0.8561	0.7096

As shown in Table 1 and Table 2, R2 values tend to 1, and SSE is not very large, indicating a good degree of fitting. In order to further explore the influence of environmental factors such as temperature and humidity [17]on the model, So let's go ahead and introduce this variable α, Define it as a competing factor after introducing an environment variable, So we get the formula:

$$\begin{cases} \dfrac{d(x_1)}{dt} = r_1 x_1 \left(1 - \dfrac{x_1}{N} - a\exp\left(\left(\dfrac{\alpha - b}{c}\right)^2\right)\sum_{i=2}^{n}\dfrac{x_i}{N}\right) \\ \vdots \\ \vdots \\ \vdots \\ \dfrac{d(x_n)}{dt} = r_n x_n \left[1 - \dfrac{x_n}{N} - a\exp\left(\left(\dfrac{\alpha - b}{c}\right)^2\right)\sum_{i=1}^{n}\dfrac{x_i}{N}\right] \end{cases}$$

In the formula, a, b and c are all measured during the growth of fungi in different environments.

3.4.2 Solution of Improved Logistic Model of Fungal Growth

Here we take a fungus and study how it grows in different environments. In Figure 8, the ambient temperature increases in each of these seven conditions(AI1-AI7), We know from the curve change in the Figure 8 above, Under the condition of AI2, the number of fungi changed the most with time, and the last stable number is also the largest. When the temperature increased gradually, the stable number of fungi increased first and then decreased under the corresponding conditions.

3.5 Fungal Habitat Model

After analyzing the competitive relationship between fungal populations, we will focus on the following question: fungal population's growth in different environments including arid, semi-arid temperate, arboreal, and tropical rain forests [6].

Firstly, we make a numerical conversion of the five envi-

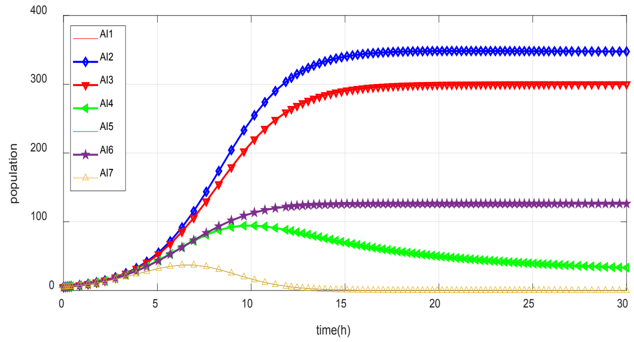


Figure 8. The number of fungi that change temperature conditions

ronments [14]. Here we introduce de Martonne dryness index [3]: two climate factors, temperature and precipitation, are used as indexes to measure five environments numerically.

$$AI = \frac{P}{T+10}$$

AI: de Martonne Aridity index, P: The mean precipitation (mm), T: The mean temperature (℃)

The standard of measurement of AI is:

Table 8. AI measure standard

AI	<10	10~20	20~30	30~40	>40
environments	*arid*	*semi—arid*	*temperate*	*arboreal*	*tropical rain forests*

According to the standard of measurement of AI, we get five environments' Aridity index:

Table 9. Aridity index of 5 different environments

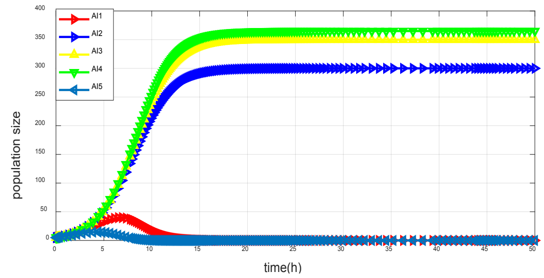
environments	*T/℃*	*P/mm*	*AI*
arid	28	180	4.7
semi — arid	25	350	14
temperate	16	750	25
arboreal	18	950	33.9
tropical rain forests	26	2500	69.4

We will predict whether different species fungi can coexist in different environments. We continue to choose the five fungus representatives: a_gal, f_fom, p_harm, p_robin, and p_sangs, as our research objects. The predicting outcomes as follows:

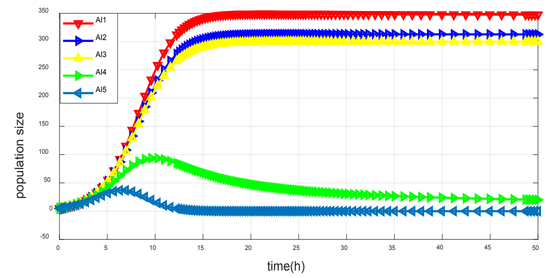
Table 10. Aridity index of 5 different environments

Environments	a_gal	f_fom	p_harm	p_robin	p_sangs
Dari	0	0	0	0	0
Semi-arid	1	1	1	0	0
Temperate	1	1	1	1	0
Arboreal	1	1	1	1	1
Tropical rain forest	0	0	0	1	0

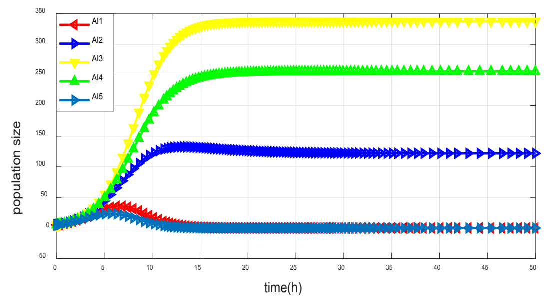
To sum up, whether fungi can coexist with each other is mainly determined by the external environment and



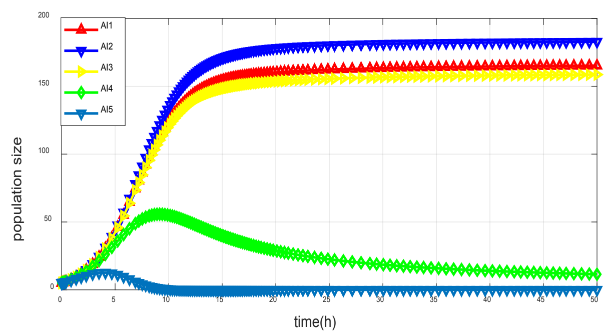
(a) a_gal's



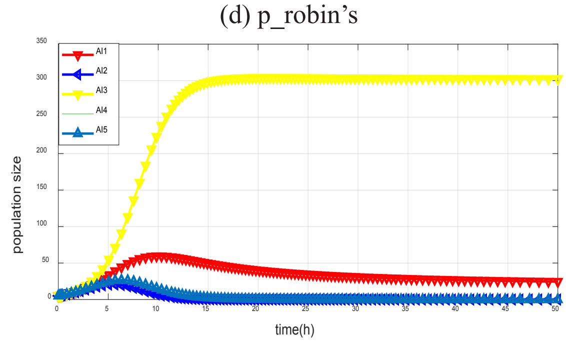
(b) f_fom's



(c) p_harm's



(d) p_robin's



(e) p_sangs's

Figure 9. Predicting outcomes

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the competitive level among fungi. When the competitive level is the same, different strains can coexist with each other under the condition of little environmental fluctuations. Therefore. for the best combination of species, it is suggested to choose two species with similar competition grades and similar classes.

3.6 Diversity Analysis

3.6.1 Relationship of Diversity of Fungal and Decomposition Rate

From Logistic-Based Fungal Growth Competition Model, we can know that there are species competition when different kinds of fungi live in a same place. In other words, the diversity of fungal communities of a system will affect the breakdown of ground litter.

According to the research of Douglas Yu et al [9], the relationship between fungal diversity and CO_2 emissions from the breakdown of ground litter is a negative correlation. The higher the fungal diversity in deadwood is, the slower the decomposition rate will be [20].

We use Niche overlap [11] to explain this conclusion. Niche overlap means the phenomenon of two or more similar species living in a same space and they compete for common resources. As shown in the Figure 10, the overlapping part in the middle area represents the same resources required by two populations living in the same community. The larger the overlapping part is, the larger Niche overlap is, and intense the interspecific competition will be more intense.

All kinds of fungi need to use nutrients in the ground litter to breed. However, these resources are usually limited. That's why there is a competition for food and living space resources among fungal populations [19].

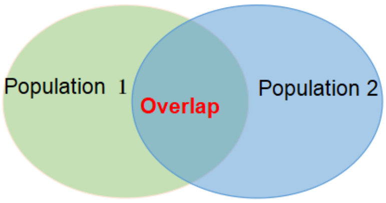

Figure 10. sketch map of the niche overlap

Every year, the world's wood decomposition produces as much CO_2 [10] as the burning of fossil fuels. Luckily, we have learned that the diversity of fungi communities of a system could slow down the decomposition rate of litter and deadwood on the ground [15]. It has a positive effect on relieving the greenhouse effect.

Fungal diversity is an important part of bio-diversity. It can be closely related to plants through mutualistic symbiosis or parasitism. It is reliable to believe that there is a coupling relationship between fungal diversity and plant diversity.

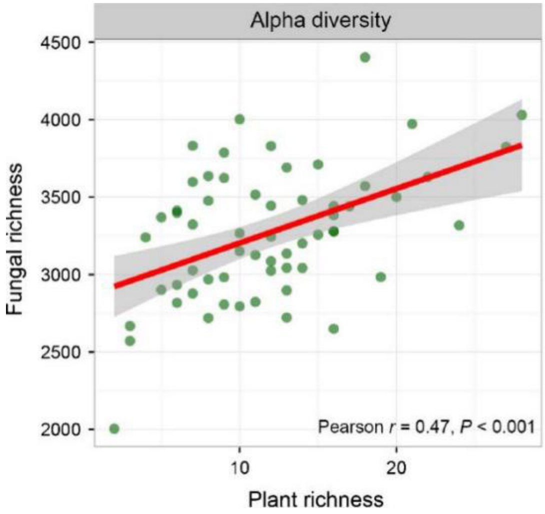

Figure 11. Alpha diversity

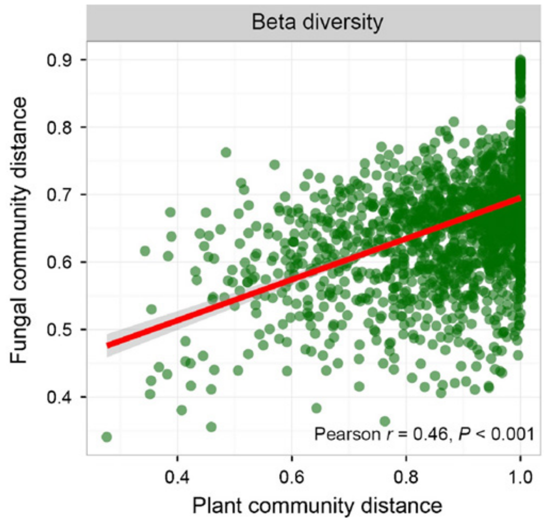

Figure 12. Beta diversity

Through the data of 60 stations in the experiment of Teng Yang et al. [3], We can get the relationship between plant richness and fungal richness, plant community distance and fungal community distance. The figure shows that there is a positive correlation between fungal diversity and plant diversity. Therefore, in ecosystem, the greater the species richness, the more stable the biological system will be, and the more organisms can be accommodated.

4. Sensitivity Analysis

For the equation we created, the most important parameter is the competition factor, Through the sensitivity test of the parameter of competition factor, the results are as follows:

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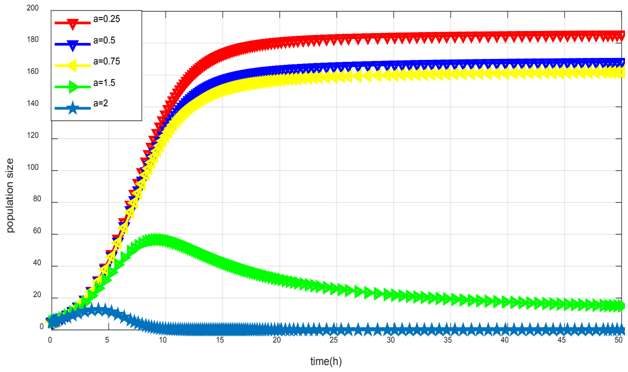

Figure 13. Sensitivity test of competitive factors

By changing the size of the competition factor we observed, that:When the competition factor changes little, the function image changes little, However, when the competition factor changes greatly, the function image changes dramatically. This phenomenon indicates that the competitive factor is sensitive and can accurately reflect the population quantity when the competitive factor changes.

5. Model Evaluation

5.1 Strengths

- During the whole modeling process, we set reasonable assumptions that: Environmental resources are limited, and there is only competition between different species. There is no other relationship. The growth of fungi is affected by many variables, but only the temperature and humidity as well as the moisture tolerance, growth rate and decomposition rate of fungi are considered. This facilitates the construction and resolution of models.
- We innovatively used analogies to add initial environmental factors to the model. This allows us to further understand the effects of weather and climate change on the model.

5.2 Weaknesses

- Our model has a lot of parameters, and the values of those parameters are mostly biological, Due to the diversity and complexity of biology, the values of these parameters can vary considerably, This can also have an impact on the accuracy of the model.

6. Conclusions

Fungi play an important role in the global material cycle, so it will be very meaningful and interesting to study its characteristics and interaction with ecosystem.

For problem 1, we choose the growth rate and the fungus' tolerance to moisture to describe the wood decomposition rate, and established Wood Decomposition Rate Model. We use Multiple linear regression equations to show the relationship between the decomposition rate of wood and the moisture tolerance and growth rate of fungi.

For problem 2, firstly, we divide the fungus samples into five categories based on the optimal growth temperature and growth humidity of each fungus. Secondly, we set up the competitive factor σ to describe the competitive relationship among the fungi population, and established the Fungal Competition Model which shows the competitive ability of various fungi.

For problem 3, we add the environmental factor α to describe fungi's real growing environment, and established the Improved Logistic Model of Fungal Growth. We examine the sensitivity of fungal populations to environmental fluctuations. Through short -term and long-term prediction trend, we can know that with the increase of temperature, the number of fungus population will decrease gradually.

For problem 4, we introduce Aridity index to describe the five habitats of fungi. We establish the Habitat Model of Fungi, and then predict the survival state of the fungal population. Finally, we obtain the best combination of fungi in five habitats.

For problem 5, we use Niche overlap to explain the negative correlation between fungal diversity and the rate of wood decomposition.

In addition, in the sensitivity analysis, we tested the competitive factor σ to analyze the effect of parameter changes on fungal population changes.

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