Mathematical model for predicting fungal growth and decomposition rates based on improved Logistic equations

Jiayong Pan[1,2†], Wenxin Le[1,3,4,5†], Zi'ao Wang[1,6,7,8], Jian Chen[1*]

(1. *College of Engineering, China Agricultural University, Beijing 100083, China*;
2. *Shenzhen Key Laboratory of Intelligent Microsatellite Constellation, Shenzhen 518107, Guangdong, China*;
3. *Key Laboratory of Spatial-temporal Big Data Analysis and Application of Natural Resources in Megacities, MNR, Shanghai 200063, China*;
4. *Key Laboratory of Urban Land Resources Monitoring and Simulation, Ministry of Natural Resources, Shenzhen 518000, Guangdong, China*;
5. *Jiangsu Province and Education Ministry Co-sponsored Synergistic Innovation Center of Modern Agricultural Equipment, Jiangsu University, Zhenjiang 212013, Jiangsu, China*; 6. *Key Laboratory of Smart Agricultural Technology in Tropical South China, Ministry of Agriculture and Rural Affairs, Guangzhou 510642, China*; 7. *State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, Beijing 100191, China*; 8. *State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310013, China*)

Abstract: As the function of the decomposition of fungi has been clearly researched in the global carbon cycle, it is obviously of value to explore the decomposition rate of fungal populations. This study analyzed the relationship between environmental factors and biodiversity step by step. In order to explore the interaction between the fungi and the relationship between the decomposition rate of fungi with time, the model based on the Logistic model was built and the Lotka-Volterra model was employed in the condition of two kinds of fungi existing in an environment with limited resources. The changing trend of population number and decomposition rate of several fungi under different environmental conditions can be predicted through the model. To illustrate the applicability of the model, *Laetiporus conifericola* and *Hyphoderma setigerum* were applied as examples. The results showed that the higher the degree of population diversity, the greater the decomposition rate, and the higher the decomposition efficiency of the ecosystem. Its rich species diversity is conducive to accelerating the decomposition of litter, lignocellulose, and the circulation of the entire ecosystem. Based on the above model and using the data from measuring the mycelial elongation rate of each isolate at 10°C, 16°C, and 22°C under standardized laboratory conditions, the growth patterns of the five fungi combinations were simulated. The results revealed a general increase in growth rate with increasing temperature, which verifies the accuracy of the model. Moreover, it also revealed that the total decomposition rate after fungal incorporation was negatively correlated with the decomposition rate of a fungal single action. Based on the above model, predictions can be made for fungal growth in different environments, and suitable environments for fungal growth can be determined. In the future, the model can be further optimized, and lignin and cellulose decomposition factors can be added to fit the decomposition of logs. The application scenarios of the model can be further broadened, which can contribute to the restoration and management of the ecological environment, as well as produce good effects in the fields of fungi assisting the global carbon cycle and soil problem restoration.

Keywords: Logistic equations, fungal decomposition, fungal growth, mathematical model
DOI: 10.25165/j.ijabe.20231601.7405

Citation: Pan J Y, Le W X, Wang Z A, Chen J. Mathematical model for predicting fungal growth and decomposition rates based on improved Logistic equations. Int J Agric & Biol Eng, 2023; 16(1): 60–65.

1 Introduction

As a significant component of life on Earth, the carbon cycle describes the process of the exchange of carbon throughout the geochemical cycle. Mycorrhiza is a symbiote formed by plant roots and mycorrhizal fungi, which is widely distributed in terrestrial ecosystems. More than 90% of vascular plant roots can form mycorrhiza[1], which can help plants absorb water, nitrogen, phosphorus, and other nutrients, promote plant growth and obtain carbohydrates from host plants to meet their own growth needs[2]. Due to the exchange of carbon sources and nutrients between mycorrhizal fungi and plants[2] significantly affecting the accumulation and transformation of soil organic carbon[3], it is essential to understand the role of mycorrhiza in the soil carbon cycle. Further, we need to understand the fungal decomposition properties. Saqib et al.[4] found the decomposition inhibition potential of CH-Fe_2O_3 NPs on *Rhizopus oryzae*. Meanwhile, Fiza et al.[5] showed the inhibition of fungal decomposition by aqueous extracts. Therefore, it is necessary to keep thorough research on fungal decomposition. When microbial community structure affects the rate of ecosystem processes, the decomposition rate is proportional to the growth rate of decomposers[6]. Understanding how the decay rate varies with the composition of fungal communities will be the key to accurately predicting terrestrial carbon dynamics, which is reflected in contemporary biogeochemical models of litter decomposition[7,8]. Aiming at improving these predictions, there is an urgent need to establish a practical and empirically proven link between fungal characteristics

Received date: 2022-02-08 **Accepted date:** 2022-09-18
Biographies: Jiayong Pan, Undergraduate student, research interest: applied mathmatics and cybernetics, Email:2019307070314@cau.edu.cn; **Wenxin Le**, Undergraduate student, research interest: applied mathematics and cybernetics, Email: lewenxin@126.com; **Zi'ao Wang**, Undergraduate student, research interest: applied mathematics and cybernetics, Email: za_wang@cau.edu.cn.
† These authors contributed equally to this work.
***Corresponding author: Jian Chen**, Professor, research interest: cybernetics and unmanned systems control. College of Engineering, China Agricultural University, Beijing 100083, China. Tel: +86-18810922501, Email: jchen@cau.edu.cn.

and their contribution to the function of ecosystems[9-11]. Maynard et al.[12] found the range of wood decomposer fungi in North America ranges from fast-growing competitive individuals to slow-growing pressure-tolerant fungi, which may establish communication between two aspects. The early researchers included microbial communities in the decomposition model and assumed that the rate of decay increased with the growth rate of decomposers[6,13,14]. On the contrary, it has long been thought that fungi with high mycelium density and slow growth may decompose wood faster than thin fungi that stretch outward at the phenotypic level[15]. Based on the above conclusions, it is necessary to research the interaction between fungi and many kinds of fungi. A logistic model is a simple (linear) model to fit the data, and the fitting process of the model is quite stable, resulting in a small variance, which may have a high deviation[16]. According to these characteristics, the popular Lotka-Volterra ecological population model proposed by Lotka[17] and Volterra[18] has been widely studied in the literature. When two or more species are together and have the same basic needs, they usually compete for resources, food, habitat, or territory. In this work, a deterministic competitive Lotka-Volterra system with populations is given. Taking the Lotka-Volterra competition model in a random environment as the research object, the dynamic changes in the population size of different species are simulated. It is proved that the growth rate of population size has an upper bound[19].

Lotka-Volterra model has been used to study the interaction between fungi[20]. Respecting the effects of ground waste and lignocellulose concentration on fungal decomposition, this study did not consider the effects of environmental capacity and temperature, and humidity in the environment. They assumed that there are only two conditions in the process of the interaction between fungi. One is that two fungi do not interfere with each other and the other one is that one fungus is completely replaced. However, through calculation, there is still the possibility that different fungal combinations may behave differently in different environments and climates.

2 Model establishment

Let the population number be P and the growth rate be h. Under ideal conditions, there is no limit to growth. Therefore, the number of fungi should satisfy Equations (1).

$$\frac{\mathrm{d}P}{\mathrm{d}t} = hP \tag{1}$$

However, the survival resources of the environment are limited in practice. Therefore, the fungus has an environmental carrying capacity K, which makes a single population in the same environment conform to the Logistic equation:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = hP\left(1-\frac{P}{K}\right) \tag{2}$$

The interspecific competition will occur when two fungal populations 1 and 2 (P_1 and P_2) are in the same environment with limited resources. Therefore, the Lotka-Volterra model can be used to establish Equation (3).

$$\begin{cases} \dfrac{\mathrm{d}P_1}{\mathrm{d}t} = h_1P_1\left(1-\dfrac{P_1}{K_1}-\alpha\dfrac{P_2}{K_1}\right) \\ \dfrac{\mathrm{d}P_2}{\mathrm{d}t} = h_2P_2\left(1-\dfrac{P_2}{K_1}-\beta\dfrac{P_1}{K_2}\right) \end{cases} \tag{3}$$

where, α represents the competition coefficient of population 2 against population 1, which means the survival resources occupied by the unit number of population 2 are equal to the survival resources occupied by α number of population 1; β represents the competition coefficient of population 1 against population 2. The product of α and β should be 1. This model can be extended to the case of multi-population competition.

In the following, the calculation process of the model parameters is optimized for the fungi that decompose lignocellulose and humus. To analyze the effects of the internal characteristics of the strains and external environmental reasons, submodels of environmental conditions affecting the growth rate and the environmental carrying capacity were established. The models were finally made to predict the population size and decomposition rate trends of several fungi under different ecological conditions. The competition between the two strains is taken as an example, which can be extended to the competition of multiple strains.

The analyzed fungi need to decompose lignocellulose and humus as the source of main nutrients[21], thus the decomposition rate of each group represents its ability to occupy survival resources. The expression of the competition coefficient and decomposition rate is given by

$$\frac{\alpha}{\beta} = \frac{d_2}{d_1} \tag{4}$$

where, d_1 and d_2 are the decomposition rate of populations 1 and 2. Therefore, the relationship between α and β can be deduced as,

$$\begin{cases} \alpha = \sqrt{\dfrac{d_2}{d_2}} \\ \beta = \sqrt{\dfrac{d_1}{d_2}} \end{cases} \tag{5}$$

The submodel for the effect of environmental conditions on the reproduction rate is developed below. Different fungi have different sensitivities to temperature and humidity[12]. Celsius temperature and water potential are used to represent ambient temperature and humidity and are normalized to map the data onto the interval [0, 1][10]. Let the ratio of the fungal growth rate at actual temperature to the maximum growth rate at the optimum temperature be the temperature suitable coefficient T for the current environment. The ratio of the fungal growth rate at the actual water potential to the maximum growth rate at the optimum water potential is the wet suitability coefficient W for the current environment.

In actual situations, slow-growing fungal strains show better resistance to environmental changes such as temperature and humidity. And strains that proliferate faster are less resistant to adverse environments[22]. Thus, the relationship between growth rate and environmental conditions in the actual environment is obtained as,

$$h_i = h_i \max \sqrt{WT} \cdot R_{\mathrm{env}}^{-h_i \max (1-WT)} \tag{6}$$

where, R_{env} is the parameter of fungal resistance to environmental changes. The fitting value is about 1.119.

Parnas et al.[6] noted that both fungal growth rate and decomposition rate are positively correlated since they reflect the activity of fungi. Lustenhouwer et al.[22] gave the corresponding data of the Hyphal extension rate (mm/d) and the Decomposition rate (percentage of mass loss in 122 d). To better match the actual trends, the natural logarithm is taken for Hyphal extension rate data. A linear regression was performed on all data, and the regression equation is obtained as:

$$d_i(h_i) = 5.8955\ln(h_i) + 16.3744 \tag{7}$$

To develop the model of environmental carrying capacity, nutritional coefficient N was introduced to represent the nutritional level of lignocellulose and humus in the environment. The amount

of lignocellulose and humus received the combined effect of the rate for plant conversion to lignocellulose and humus and the microbial decomposition ability. Thus, it may lead to the total amount of humus in permafrost tundra being greater than that of the tropical rainforest. However, tropical rainforests provide more nutrients for fungi compared to permafrost tundra. Therefore, nutrient coefficient N is defined by employing phytomass rather than the total amount of humus[23,24]. If the phytomass in the environment is M (kg/m^2), then,

$$N = 0.577\sqrt{M} \tag{8}$$

To calculate the environmental carrying capacity K, it is considered that environmental carrying capacity is determined by two factors, including the fungal decomposition rate, and the environmental nutrient coefficient. The unit of K is mm/m^2, then,

$$K_i = \frac{N}{d_i} \tag{9}$$

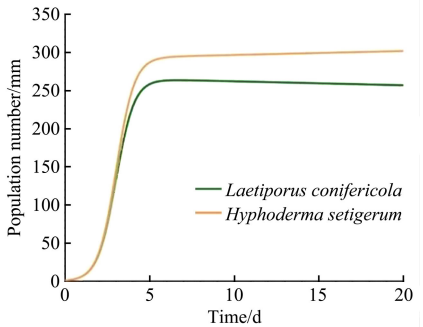
By bringing the data obtained from Equations (5), (6), and (9) into Equation (3), differential equations for the number of populations can be obtained. The total decomposition rate of fungi in the environment is

$$D = d_1P_1 + d_2P_2 \tag{10}$$

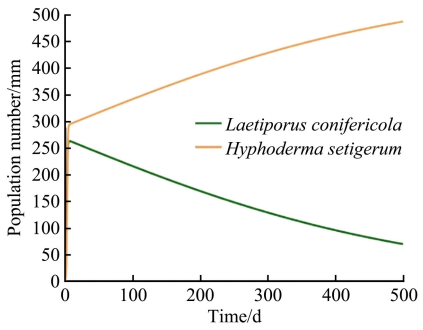
To show the applicability of the model, the following is an example of *Laetiporus conifericola* and *Hyphoderma setigerum* to calculate the competition between the two populations. Take the temperate continental climate with an ambient temperature of 21°C, a water potential of −1.5 MPa, and a phytomass of 3 kg/m^2. The population number of *Laetiporus conifericola* is P_L, and that of *Hyphoderma setigerum* is P_H. The number of two populations can be expressed as,

$$\begin{cases} \dfrac{dP_L}{dt} = 2.509P_L\left(1 - \dfrac{P_L}{559.697} - 1.002\dfrac{P_H}{559.697}\right) \\ \dfrac{dP_H}{dt} = 2.553P_H\left(1 - \dfrac{P_H}{557.078} - 0.998\dfrac{P_L}{557.078}\right) \end{cases} \tag{11}$$

Plotting the change in the number of two populations:



a. 20 d



b. 500 d

Figure 1 Groups number change diagram

The total decomposition amount tended to increase in the early stage and gradually stabilized in the later stage. And when the number of fungal populations increases, the total decomposition in the stable period will also increase. Thus, we found that the richer the population diversity, the greater the decomposition rate and the higher the overall efficiency of the ecosystem. Its rich species diversity is conducive to accelerating the decomposition of litter, lignocellulose, and the circulation of the entire ecosystem.

3 Results and discussion

3.1 Result analysis

In this section, based on the above model and the data on the mycelial elongation rate of each isolate measured at 10°C, 16°C, and 22°C under standardized laboratory conditions[22], the growth patterns of the five fungi combinations were simulated. For the convenience of the research, we kept the same parameters as in the previous section. Then, fungi combinations in similar regions were selected for analysis, and the growth rates of the selected fungi at three characteristic temperatures were employed as the initial value of the model to predict the environmental capacity of each fungus, resulting in Table 1. The results revealed that the changing pattern of environmental accommodation of fungi are at different temperatures and showed that there is a reversal of the dominant bacterial species at the temperatures, which is because the growth characteristics of fungi and temperature are closely related, and the fungus with a greater growth rate at a certain characteristic temperature is more likely to be the dominant strain in competition.

Table 1 Environmental capacity

Fungus combination	Environmental capacity/mm		
	10°C	16°C	22°C
(A) *Hyphoderma setigerum*+*Laetiporus conifericola*	11.59 724.53	29.83 520.35	89.91 452.59
(B) *Armillaria tabescens*+*Fomes fomentarius*	347.40 1035.20	230.00 1217.50	6.85 479.66
(C) *Porodisculus pendulus*+*Phellinus robiniae*	758.61 12.80	645.19 148.01	159.41 519.38
(D) *Mycoacia meridionalis*+*Merulius tremullosus*	1.78 520.74	2.80 455.12	2.72 418.86
(E) *Schizophyllum commune*+*Tyromyces chioneus*	280.79 601.35	246.78 517.74	432.75 80.92

Similarly, the growth rates at the three characteristic temperatures were analyzed. For comparison, a weighted average of the growth rate obtained from the simulation was performed to obtain the results in Table 2. The results showed a general increase in growth rate with increasing temperature and indicated that the weighted growth rate is similar to that of the dominant bacteria, as the inferior bacteria were largely eliminated while only the dominant bacteria existed at the later stage of the simulation.

Table 2 Single growth rate and weighted growth rate

Fungus combination	Independent growth rate/%			Weighted extension rate/%		
	10°C	16°C	22°C	10°C	16°C	22°C
A	0.44 1.08	1.90 3.31	4.68 6.00	1.08	3.30	5.97
B	0.32 0.36	0.68 1.28	1.56 4.62	0.35	1.27	4.62
C	0.95 0.40	1.25 1.52	2.90 3.32	0.95	1.48	3.25
D	0.36 3.3	1.10 5.85	1.60 8.67	3.29	5.84	8.67
E	1.88 1.92	3.32 3.37	7.40 5.67	1.90	3.35	7.38

Next, the total decomposition rate of the fungal group was analyzed, and the rate of fungi in the environment is

$$D = d_1P_1 + d_2P_2 \tag{10}$$

Thus, the total decomposition rate and arrival days are obtained and listed in Table 3. The total decomposition rate of each fungus combination in the table gradually stabilized and approached 1 after a period, which indicated that the amount of vegetation produced was in basic balance with the amount of decomposition by the fungi, and the best decomposition effect was reached at this time. However, the time for different fungal combinations to reach the optimal decomposition rate is different, which is related to the growth rate of fungi. And the growth rate is negatively correlated with time. The longest is the combination of Armillaria tabescent and Fomentarius, which takes 35 d to reach decomposition equilibrium at a characteristic temperature of 10°C; the shortest is the combination of *Mycoacia meridionalis* and *Merulius tremullosus*, which takes only 4 d, 3 d, and 2 d to reach the decomposition equilibrium at the three types temperatures. In addition, the time to reach decomposition equilibrium gradually decreased with increasing temperature, which was consistent with the conclusion that the growth rate generally increased with increasing temperature and verified the accuracy of the model.

Table 3 Total decomposition rate and arrival days

Fungus combination	Total decomposition rate/%			Maximum days/d		
	10°C	16°C	22°C	10°C	16°C	22°C
A	99.97	99.95	99.94	12	3	2
B	99.96	99.98	99.93	35	10	3
C	99.98	99.99	99.97	13	7	4
D	99.94	99.93	99.93	4	3	2
E	99.94	99.93	99.94	6	4	2

In this part, the relationship between the decomposition rate of the fungus in a single action and the rate in combination was analyzed, and Table 4 was obtained herein. The results showed that with the increase in temperature, the decomposition rate of fungal single action had an increasing tendency. The highest was *Merulius tremullosus*, whose single-action rate can reach 53.5% at 22°C. The lowest was *Schizophyllum commune* with a single action rate of 2.02% at 10°C. In addition, the results also revealed that the increase in the total decomposition rate of the combination decreased gradually with the increase in temperature. As the total decomposition rate has been stable, the decomposition rate of the fungus has increased. The highest lifting factor was the combination of *Hypoderma setigerum* and *Laetiporus conifericola*, up to 37.44 times; the lowest lifting factor was the combination of *Mycoacia meridionalis* and *Merulius tremullosus*, which was 1.87 times at 22°C. The overall results revealed that the lower the decomposition rate of the fungus in a single action, the higher the increase in the total decomposition rate in combination.

Table 4 Combination decomposition rate improvement effect

Fungus combination	Independent decomposition rate%			Lifting multiple		
	10°C	16°C	22°C	10°C	16°C	22°C
A	2.67±1.02 2.29±0.19	5.63±0.61 20.28±9.79	18.82±9.96 7.60±7.49	37.4	4.9	5.31
B	2.83±0.59 10.41±1.8	3.67±1.37 21.26±11.9	12.75±2.78 47.24±28.68	9.6	4.7	2.12
C	2.61±0.58 3.68±0.49	2.43±0.55 4.52±0.96	4.36±0.51 8.28±4.79	27.2	22.1	12.1
D	2.16±1.01 22.78±2.58	5.67±1.35 32.27±9.91	7.96±1.21 53.5±4.78	4.4	3.1	1.9
E	3.92±1.24 5.35±1.46	2.02±2.07 16.74±3.65	12.69±3.52 29.06±9.35	18.6	5.9	3.44

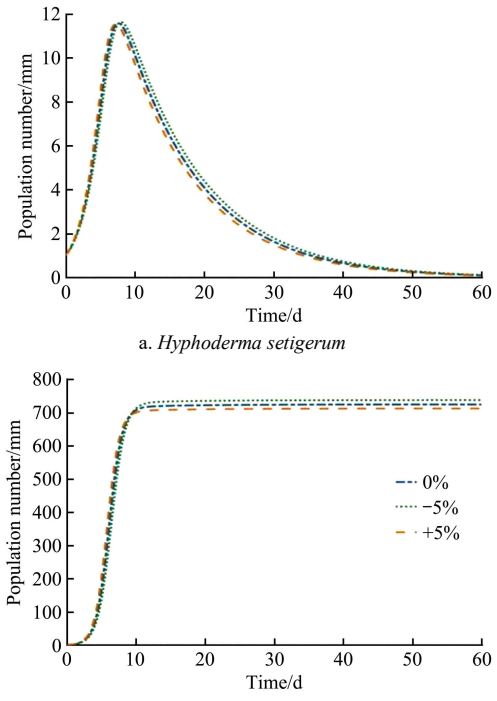
3.2 Discussion

A model correctness test[12] based on the real value of the mycelial density of the fungus was performed, simulating the environmental adaptability of the fungus, and the results are listed in Table 5. Specifically, fungi occurring in nearby locations were selected as combinations, applying *Porodisculus pendulus* (43.550150°N, 89.756867°W) and *Phellinus robiniae* (43.013434°N, 89.737043°W) as an example, the growth rate at 16°C selected according to the optimum temperature of the two fungi was brought into the model to calculate the ratio of the number of populations of the combination and was compared with the ratio of the number of populations calculated by the true value. Similarly, the data of the other four groups were obtained. As illustrated in Table 5, the ratio of fungal environmental accommodation calculated by the model and the ratio of true values of the two mycelial densities were in high agreement, thus proving the correctness of the model.

Table 5 Ratio of the number of communities in the fungal group calculated by the model and the true value

Fungus combination	Environmental capacity/mm	Population ratio	Truth value /$\mu g \cdot cm^2$	Population ratio
Porodisculus pendulus+ *Phellinus robiniae*	645.1969 148.0104	4.3591	0.32 0.07	4.5714
Armillaria gallica+ *Xylobolus subpileatus*	21.1527 675.5387	0.0313	0.10 1.74	0.0574
Merulius tremellosus+ *Phlebiopsis flavidoalba*	136.6185 401.0236	0.3407	0.02 0.04	0.5
Armillaria gallica FP102534 A5A + FP102535 A5D	310 1386	0.2237	0.16 0.50	0.32
Phlebia acerina+ *Pycnoporus sanguineus*	420.4402 28.5904	14.7056	0.27 0.02	13.5

Further, different initial values were substituted into the model for testing. Specifically, taking *Hyphoderma setigerum* and *Laetiporus conifericola* as an example, the initial growth rate was adjusted up and down at a ratio of 5%, which was substituted into the model at a characteristic temperature of 10°C and the results are shown in Figure 2. The trend of the fungal populations was stable when the initial values were changed, indicating the stability



a. *Hyphoderma setigerum*

b. *Laetiporus conifericola*

Figure 2 Population characteristics of the growth rate change ±5% fungus group and the original growth rate value (i.e. 0% group)

of the model. Specifically, the results showed that when the growth rate increases, the environmental capacity tends to decrease. As the growth rate and the population number are negative correlations when the plant quantity is constant, it further illustrates the accuracy of the model.

Furthermore, the stability verification of the model was performed through the selected five fungi combinations and Table 6 was obtained. The results illustrated that when the initial value of the model changed by 5%, the maximum relative error was 2.64% for the *Armillaria tabescens* and *Fomes fomentarius* group while the smallest relative error was 0.01% for the *Mycoacia meridionalis* and *Merulius tremullosus* group. It is because the relative change increases with the change of initial value when the number of populations increases. However, none of the relative errors exceeded 3%, thus proving the accuracy and reliability of the model.

Table 6 Analysis of relative deviation of environmental capacity with initial value change of 5%

Fungus combination (10°C)	Environmental capacity/mm			Relative deviation rate%	
	−5%	0%	5%	−5%	5%
A	11.63	11.59	11.55	0.35	0.35
	737.71	724.54	712.30	1.82	1.69
B	356.2	347.4	339.5	2.53	2.27
	1062.5	1035.2	1010.8	2.64	2.36
C	773.14	758.62	745.28	1.91	1.76
	12.86	12.80	12.75	0.44	0.43
D	1.78	1.78	1.78	0.01	0.01
	527.56	520.75	514.43	1.31	1.21
E	284.97	280.79	276.93	1.49	1.38
	610.13	601.36	593.22	1.46	1.35

4 Conclusions

The present study investigated the competition between fungal populations and the decomposition rate in the case of fungal combinations and gave the conditions for the two fungi to become the dominant species when they competed by applying the Lotka-Volterra mathematical model. The fungal growth data under standard laboratory conditions were utilized to fit the model parameters, which showed that the total decomposition amount tended to rise in the early stage and gradually stabilized in the later stage. The study also found that the richer the population diversity, the greater the decomposition rate. Extensively, the model in this study was also applicable to the simulation of competition among various fungi, which has instructive significance for ecological research. In the future, the model can be optimized, and added lignin and cellulose decomposition factors to fit the decomposition of logs and further broaden the application scenarios of the model, which can contribute to the restoration and management of the ecological environment, as well as produce good effects in the fields of fungi assisting the global carbon cycle and soil problem restoration.

Acknowledgements

This work was financially supported in part by the National Key Research and Development Program of China (Grant No. 2022YFD2001405); in part by the Key Laboratory of Spatial-temporal Big Data Analysis and Application of Natural Resources in Megacities, MNR (Grant No. KFKT-2022-05); in part by the Open Fund of Key Laboratory of Urban Land Resources Monitoring and Simulation, Ministry of Natural Resources (Grant No. KF-2021-06-115); in part by the National Natural Science Foundation of China (Grant No. 51979275); in part by the Open Project Program of Key Laboratory of Smart Agricultural Technology in Tropical South China, Ministry of Agriculture and Rural Affairs (Grant No. HNZHNY-KFKT-202202); in part by the Open Project Program of State Key Laboratory of Virtual Reality Technology and Systems, Beihang University (Grant No. VRLAB2022C10); in part by the Jiangsu Province and Education Ministry Co-sponsored Synergistic Innovation Center of Modern Agricultural Equipment (Grant No. XTCX2002); in part by the State Key Laboratory of Clean Energy Utilization (Open Fund Project No. ZJUCEU2022002); in part by Shenzhen Science and Technology Program (Grant No. ZDSYS20210623091808026); in part by the Earmarked Fund (CARS-20); and in part by the 2115 Talent Development Program of China Agricultural University.

[References]

[1] Brundrett M C. Mycorrhizal associations and other means of nutrition of vascular plants: Understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. Plant & Soil, 2009; 320: 37–77.

[2] Smith S E, Read D J. *Mycorrhizal Symbiosis*. Quarterly review of biology, 2008; 3(3): 273–281.

[3] Liang C, Amelung W, Lehmann J, Kästner M. Quantitative assessment of microbial necromass contribution to soil organic matter. Global Change Biology, 2019; 25(11): 3578–3590.

[4] Saqib S, Zaman W, Ullah F, Majeed I, Munis M F H. Organometallic assembling of chitosan-Iron oxide nanoparticles with their antifungal evaluation against *Rhizopus oryzae*. Applied Organometallic Chemistry, 2019; 33(11): e5190. doi: 10.1002/aoc.5190.

[5] Liaquat F, Liu Q L, Arif S, Haroon U, Saqib S, Zaman W, et al. Isolation and characterization of pathogen causing brown rot in lemon and its control by using ecofriendly botanicals. Physiological and Molecular Plant Pathology, 2021; 114(1): 101639. doi: 10.1016/j.pmpp.2021.101639.

[6] Parnas H. Model for decomposition of organic material by microorganisms. Soil Biology and Biochemistry, 1975; 7(2): 161-169.

[7] Allison S D, Goulden M L. Consequences of drought tolerance traits for microbial decomposition in the DEMENT model. Soil Biology and Biochemistry, 2017; 107: 104–113.

[8] Wieder W R, Grandy A S, Kallenbach C M, Taylor P G, Bonan G B. Representing life in the Earth system with soil microbial functional traits in the MIMICS model. Geoscientific Model Development Discussions, 2015; 8(2): 1789–1808.

[9] Malik A A, Martiny J, Brodie E L, Martiny A C, Allison S D. Defining trait-based microbial strategies with consequences for soil carbon cycling under climate change. The ISME Journal, 2020; 14(1): 1–9.

[10] Crowther T W, Van Den Hoogen J, Wan J, Mayes M A, Keiser A D, Mo L, et al. The global soil community and its influence on biogeochemistry. Science, 2019; 365(6455): eaav0550. doi: 10.1126/science.aav0550.

[11] Hall E K, Bernhardt E S, Bier R L, Bradford M A, Boot C M, Cotner J B, et al. Understanding how microbiomes influence the systems they inhabit. Nature Microbiology, 2018; 3(9): 977–982.

[12] Maynard D S, Bradford M A, Covey K R, Lindner D, Glaeser J, Talbert D A, et al. Consistent trade-offs in fungal trait expression across broad spatial scales. Nature Microbiology, 2019; 4: 846–853.

[13] McGuire K L, Treseder K K. Microbial communities and their relevance for ecosystem models: Decomposition as a case study. Soil Biology and Biochemistry, 2010; 42(4): 529-535.

[14] Walse C, Berg B, Sverdrup H. Review and synthesis of experimental data on organic matter decomposition with respect to the effect of temperature, moisture, and acidity. Environmental Reviews, 1998; 6(1): 25–40.

[15] Boddy L. Fungal community ecology and wood decomposition processes in angiosperms: From standing tree to complete decay of coarse woody debris. Ecological Bulletins, 2001; 49: 43–56.

[16] Landwehr N, Hall M, Frank E. Logistic model trees. Machine Learning, 2005; 59: 161–205.

[17] Lotka A J. Elements of physical biology. Science Progress in the Twentieth Century, 1926; 21(82): 341-343.

[18] Volterra V. Variations and fluctuations of the number of individuals in animal species living together. ICES Journal of Marine Science 1928;

3(1): 3–51.

[19] Zhu C, Yin G. On competitive Lotka-Volterra model in random environments. Journal of Mathematical Analysis and Applications, 2009; 357(1): 154–170.

[20] Liu C Y, Liu Z R, Chen W F. Analysis of interaction between fungi and environment based on Lotka-Volterra model. IOP Conference Series: Earth and Environmental Science, 2021; 804(4): 042035. doi: 10.1088/1755-1315/804/4/042035.

[21] Yadav V, Malanson G. Progress in soil organic matter research: litter decomposition, modelling, monitoring and sequestration. Progress in Physical Geography: Earth and Environment, 2007; 31(2): 131–154.

[22] Lustenhouwer N, Maynard D S, Bradford M A, Lindner D L, Crowther T W. A trait-based understanding of wood decomposition by fungi. Proceedings of the National Academy of Sciences, 2020; 117(21): 11551–11558.

[23] Walker M D, Ingersoll R C, Webber P J. Effects of interannual climate variation on phenology and growth of two alpines forbs. Ecological Society of America, 1995; 76(4): 1067–1083.

[24] Stuart Chapin III F, Johnson D A, McKendrick J D. Seasonal movement of nutrients in plants of differing growth form in an Alaskan tundra ecosystem: Implications for herbivory. The Journal of Ecology, 1980; 68(1): 189–209.