Modeling and Analysis of the effect of fungal growth and decomposition on Land Environment

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Abstract: As an important part of soil ecosystem, the existence and diversity of fungi directly or indirectly affect plant diversity and ecosystem functions. Researchers study the characteristics of different fungi. Focus on the growth rate and moisture resistance of fungi, the aim of this report is to build a growth and decomposition model of fungi to evaluate the influences of fungi on the environment, atmosphere, and ecosystems. We are expected to model the decomposition of woody fibers in a certain patch of land, and do so in the presence of various types of fungi breaking down woody fibers on the identical land. In this paper, Focused on the growth rate and moisture resistance of fungi. we used cellular automata to build fungus decomposition and growth model Using data from the given literature, we clustered 34 fungi and selected the most representative fungi among the three types. The birth, growth, hyphal density, temperature, moisture, and death of fungi are considered in the model. We established a death rule related to the age of fungi and a decomposition rule related to hyphal density. The competition rule is related to the competition ranking and the number of fungus. The randomness of competition is increased through the roulette algorithm We concluded that in the beginning, C4B fungus had a competitive advantage and occupied the most resources. Due to the competition of other species, the competitive advantage of C4B fungus is gradually (about 200 days later) replaced by C8H fungi.

1. Introduction

Fungi play one of the most significant roles in the ecosystem through functioning as a primary decomposer. The carbon cycle describes the process of the exchange of carbon throughout the geochemical cycle of the Earth, and is a vital component for life on the planet. Part of the carbon cycle includes the decomposition of compounds, allowing carbon to be renewed and used in other forms. One key component of this part of the process is the decomposition of plant material and woody fibers.

In order to model the decomposition of woody fibers in each patch of land in the presence of multiple types of fungi breaking down woody fibers in the same area, we will explore the relationship of the two traits of interest, growth rate and moisture tolerance, with the rate of decomposition.

We will also investigate how the different fungi interact and decompose ground litter in a fixed patch of land in different environments based on the traits we verified and analyze how will the decomposition be impacted over time as conditions vary and the variance trend. The impact the long-term dynamics with respect to decomposition, as well as competition between fungi in each environment also require us to estimate for the decomposition rates with the given the growth rate.

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

Problem 1: Analyze the fungal activity in the presence of multiple species of fungi to build a mathematical model that describes the breakdown of ground litter and woody fibers.

Problem 2: Investigate the interactions between different species of fungi based on the model we established, which have different growth rates and different moisture tolerances.

2. Literature review

Review 1: A trait-based understanding of wood decomposition by fungi

Fungi, as the main decomposers of organic material in terrestrial ecosystems, are important promoters of the global carbon cycle. However, people's ability to link fungal community composition to ecosystem functions is limited by our understanding of the factors that contribute to different wood decomposition rates in fungi. In the article, the researchers combined the analysis of the characteristics of 34 saprophytic fungi from North America in the laboratory with 5 years of field research to study which characteristics best explain the fungus's ability to decompose. Under laboratory conditions, the growth rate of fungi (hyphae expansion rate) is the strongest single predictor of fungal-mediated wood decomposition rate, accounting for 27% of the in-situ changes in field decomposition. In summary, these results indicate that the decomposition rate is highly consistent with the historical trade-offs of tolerance life span previously found in these strains, forming a spectrum from slow-growing, stress-tolerant fungi to decomposition products to fast-growing, highly competitive with rapid fungal decomposition rates. This study shows how an understanding of the variation of fungal traits can improve early and mid-term predictions of wood decay. By mapping the results to a biogeographical distribution weighed by the tolerance of dominance throughout North America, a broad pattern of wood decomposition rates mediated by intrinsic fungi can be derived.

Review 2: Consistent trade-offs in fungal trait expression across broad spatial scales

In the article, the researchers used a feature-based method to quantify the niches of 23 basidiomycete wood-rot fungi from North America, and to study the relationship between functional trait expression, climate, and phylogeny. The analysis revealed a basic trade-off between abiotic stress tolerance and competitive ability, in which fungi with wide heat and water levels showed lower displacement ability. How much of this advantage-tolerance tradeoff is related to the environmental conditions under which the fungi are collected, in which thermal niche traits show the strongest climatic relationship. However, the dominant tolerance patterns of water and heat show opposite phylogenetic signals, indicating that these trends are affected by the combination of niche ranking along the taxonomic line and individual level adaptation and adaptation. Overall, the paper reveals key insights into the life history strategy of saprophytic fungi, showing consistent trait compromises on a wide spatial scale. Our Work

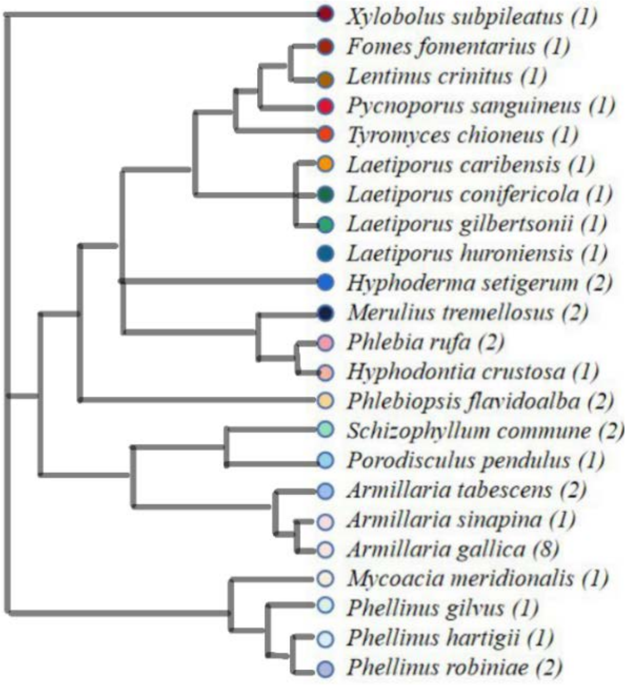

Figure 1. Fungi K-clustering graph

3. Fungus growth and decomposition model

3.1 Data preprocessing

3.1.1 The selection of the fungus

We used the phylogeny of the 20 fungal species for each fungus for which all the data used in the given reference, with the number of unique isolates per species indicated in brackets. We used the K-clustering algorithm to classify three types of fungi from more than 20 kinds of fungi in the reference literature according to their biological similarity.

We can conclude that fungi are briefly divided into three categories, we chose three representative species (A11A&C4H&C8B) of fungi from three different categories.

Table 1. The name of the selected fungus

abbreviation	The full name
A11A	Xylobolus subpileatus FP102567 A11A
C4H	Phellinus gilvus HHB11977 C4H
C8B	Laetiporus conifericola HHB15411 C8B

3.1.2 Data normalization process

Different evaluation indicators often have different dimensions and dimensional units, which will affect the results of data analysis. In order to eliminate the dimensional influence among indicators, it is necessary to conduct data standardization processing to solve the comparability between data indicators. After data standardization processing, all indicators of the original data are in the same order of magnitude, which is suitable for comprehensive comparative evaluation. The deviation standardization is a linear transformation of the original data, so that the resulting value is mapped to between [0-1]. We conducted data normalization for the competitive ranking of fungi and the influence of water potential on the growth rate. We conducted data normalization for the competitive ranking of fungi and the influence of soil water potential on the growth rate. These raw laboratory data are from references.

$$\lambda^* = \frac{\lambda - \min}{\max - \min} \tag{1}$$

3.2 Fungal growth and decomposition model

3.2.1 The establishment of the model

We used the cellular automata model to simulate fungal decomposition. This theoretical modeling started in the 1990s [5, 6]. The diffusion simulation of biological community based on cellular automata model is also a hot issue of application at present. People apply the theory of cellular automata to the study of biological community, which uses discrete spatiotemporal and state variables to define the evolution rules of community, and reveals the development rules through the average of many samples. Because environmental elements are discrete in nature, using cellular automata theory to study ecology avoids the approximate process of discrete - continuous - discrete, so it has its unique advantages. At present, the cellular automata have been widely used in the simulation of ecological dynamic processes, showing satisfactory dynamic effects.

The environment in which fungi live is equivalent to a 100×100 cell grid. Three fungi are randomly distributed in the grid at the beginning, in which each grid has natural resources available for the survival of fungi. And we assume that natural resources are abundant (Assumtion 4), so the three fungi will compete for resources to survive. We simulate the growth of the three fungi by setting up a series of rules. Finally, by adjusting the parameters, to achieve the steady-state environment. As for the composition of cellular automata, it can be regarded as a quaternion:

$$C=\left(L_{\alpha}, S, N, \mathrm{F}\right) \tag{2}$$

L_{α} is the cellular space, S is the state set, N is the neighbor, and F is the evolution rule. The rules established by referring to Penna model [2] are as follows:

1. **L_{α} (Cellular space)**

Cell is the basic unit of cellular automata. The smallest unit directly involved in the iteration of evolutionary rules is the cell. For intuitive expression and convenience of understanding, in the following part of this paper, we used a two-dimensional square grid to simulate the habitat unit of fungus growth. The environment in which fungi live is equivalent to a 100×100 cell grid. The length of each grid is 1nm.

2. **S (state set)**

Each habitat was occupied by three kinds of fungi at random, and three different numbers were used to represent the three kinds of fungi in the cell, and three numbers appeared at random in each cell.

3. **N (he neighbors)**

Considering the growth conditions of fungi, we adopted the cellular neighbors with Moore structure. For a particular cell, around eight cells are its neighbors. This is shown in Figure 2.

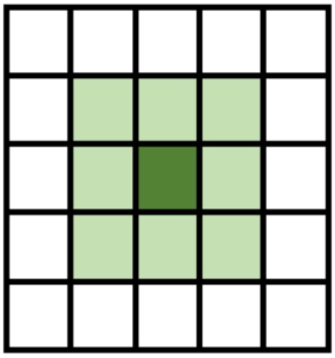

Figure 2. Neighbors of cells

4. **F (The evolution rule)**

In a classical cellular automaton, the state of a cell at the current moment is always related to its own state and the state of its neighbor at the previous unit time.

- **The natural growth rules of fungi**

According to the literature, the diameter of the fungus is usually 0.02-0.05mm. We assume that the fungal hyphae grow 0.03mm a day.

Only when the fungus completely fills a cell grid can the fungus continue to extend outward. Fungi encounter a degree of environmental resistance as they spread into surrounding Spaces that are not colonized. That is, fungi tend to grow in clusters, rather than growing alone into unoccupied space. We assign a value of 0.05 for environmental resistance per unit of empty land.

- **The rules of competition for fungi**

In habitats, because fungi have different competitive abilities, there may be a situation where the competitive fungi take up more environmental resources, thus affecting the growth of other species. We used the data given in the reference literature [3] -- competitive ranking as the embodiment of competitive ability.in order to prevent fungi with lower competition ranking from being eliminated directly, we introduced the Roulette Algorithm here. The probability of fungal reproduction in an unopposed habitat correlates with the number of fungi in the vicinity of the site and fungal competition.

$$P\left(\chi_i\right) = \frac{\varphi\left(\chi_i\right)}{\sum_{i=1}^{3} \varphi\left(\chi_j\right)}$$
$$\varphi\left(\chi_i\right) = CR_i \bullet n_i \tag{3}$$

The fungal propagation and expansion do not occupy the whole cell at one time, but slowly occupy the cell according to the growth cycle of the fungus. When the cells are fully occupied, the fungi begin to decompose the dead branches and leaves at the maximum rate of decomposition.

- **The rules of death for fungi**

With the growth of fungal age, the mortality of fungi increases, and they die when they reach the upper age limit. Fungal mortality is also related to natural mortality. The formula for mortality is shown below:

$$P\left(d_i\right) = r \times \frac{1 - age_{now}}{age_{\max}} \tag{4}$$

- **The rules of decomposition for fungi**

We call the area occupied by a unit cellular fungus the fungal density. When the fungus fills an entire cell, the fungus density of the cell becomes 1. The growth time of fungi on the grid depends on the growth rate, so the growth rate indirectly affects the decomposition rate.

$$D = \beta_{temp} \bullet \eta \tag{5}$$

3.3 The solution of the model

The parameters of the model are as follows: Competitive ranking of three fungi; Average decomposition rates at three temperatures; Fungi have a natural mortality rate of 0.8 and a birth rate of 0.6.

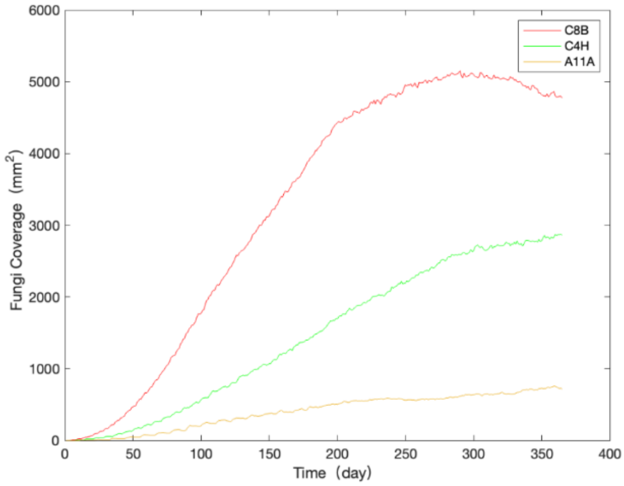

Figure 3. Short-term competition in fungi

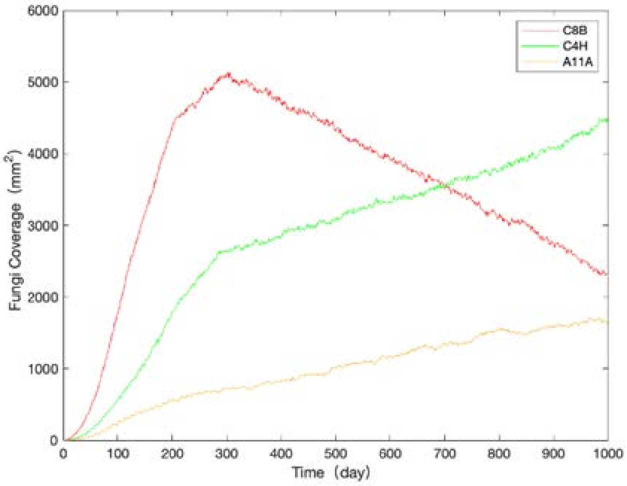

Figure 4. Long-term competition in fungi

In the short term, all the fungi are trying to survive and take over resources. The overall coverage rate of the three fungus showed an increasing trend. The C8B fungus takes up the most living space and the A11H fungus takes up the least. In the long run (about 300 days later), the C8B fungus is defeated in the competition and its occupation of living resources declines. However, the C4H fungus has become tenacious and robbed a lot of living space. The A11A fungus remains on a steady upward trend.

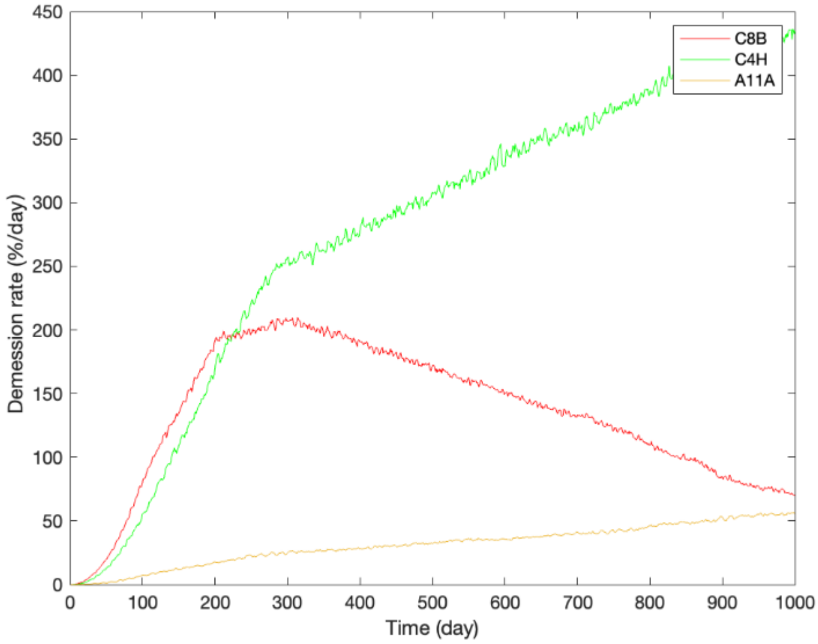

Figure 5. Decomposition rate of different periods

Based on the results of the model (as shown in Figure 5), we can draw some conclusions. In the short term (about the first 200 days), the C8B fungus is the most competitive. A11A fungus had the weakest competitive ability. In the long run, A11A fungus has a weak competitiveness but keeps a slow and stable growth. The decomposition rate of C8B fungus reached the maximum and was limited by other strains. The C4H fungus gradually replaced the C8B fungus. The decomposition rate of C8B fungus decreased while that of C4H fungus increased rapidly.

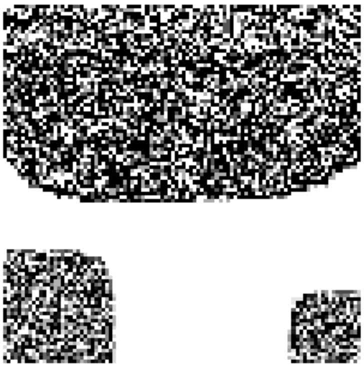

Figure 6. On day 291, the fungal coverage of the unit cell

Figure 7. On day 41, the coverage of unit cell fungi

Figure 6 and Figure 7 more intuitively reflect the coverage of the three fungi. Over time, fungi continue to grow.

4. Sensitivity analysis

Table 2. Sensitivity test parameters

Model	SSE	R^2	Adjusted R^2	RMSE
Temperature Decomposition rate	1.453	0.9347	0.8099	1.567
	11.05	0.9914	0.9657	3.324
	2.668	0.9604	0.8414	1.633
Temperature Extension rate	0.03921	0.9985	0.9941	0.198
	0.737	0.9199	0.6796	0.8585
	0.003937	0.9964	0.9855	0.06275
Water potential Extension rate	0.01792	0.9744	0.8976	0.1339
	0.01328	0.981	0.9241	0.1152
	0.007511	0.9893	0.9571	0.08666

The table 2 is the significance test of the fitting curve, including nine Models. There are three models for each fungus. All the values of R-square are stable above 90 percent. At the same time, the values of Adjusted R-square are also stable above 80 percent. Both SSE and RMSE are all stable in the single digits. In conclusion, the data show an excellent degree of fitting.

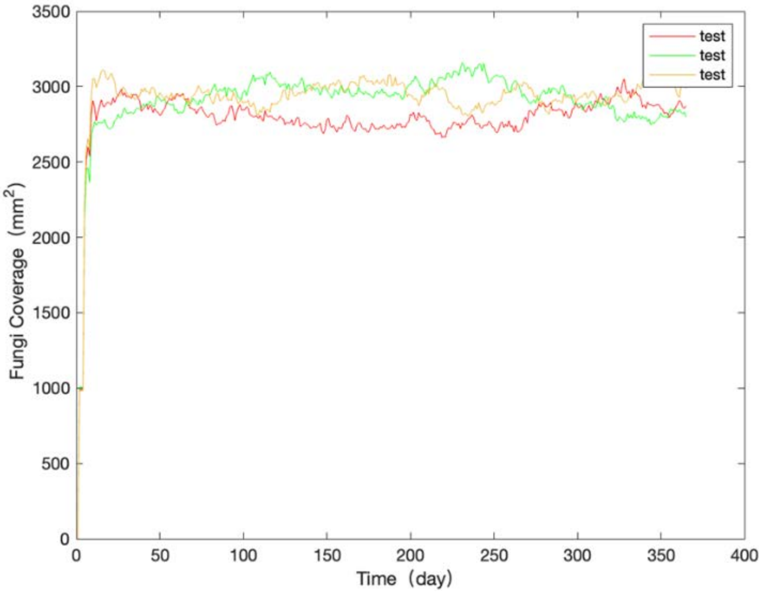

Figure 8. Sensitivity Analysis of Fungi Coverage

Based on the combined environmental condition evaluation standard we previous discussed, we performed a sensitivity analysis to test the stability of our model.

To evaluate the consistency among three fungi we chose before, the variances of fungi coverage condition at different periods of their life cycle are analyzed and presented (Figure 8).

The result reveals that three fungi share a very similar trend, fluctuating around 2750~3000 considering time differences, which suggests that the three fungi belong to the same type, confirming our hypothesis and that the coverage evaluation model is very accurate and stable.

References

[1] ZHANG Weizhen, DUAN Tingyu. Effects of two kinds of AM fungi on Vicia sativa powdery mildew [J] Ecological Science, 2020, 39 (2): 82-89. DOI: 10.14108/j.cnki.1008-8873.2020.02.011.

[2] Danuta Makowiec. Penna model of biological aging on a lattice[J]. Physica A-Statistical Mechanies and Its Applications, 2001, 289 (1-2): 208 - 222.

[3] Nicky Lustenhouwer, Daniel S. Maynard, Mark A. Bradford, Daniel L. Lindner, Brad Oberle, Amy E. Zanne, and Thomas W. Crowther, "A trait-based understanding of wood decomposition by fungi," Proceedings of the National Academy of Sciences of the United States, May 13, 2020.

[4] Argollo de Menezes M, Racco A, Penna TJP. Why trees live longer[J]. Physica A, 1996, 233 (2): 132 – 139.

[5] Nagel, K., Schreckenberg, M., A cellular automaton model for freeway traffic. Journal of Physique I, 1992, 2 (12): 2221 – 2228.

[6] Biham, O., Middleton, A.A., Levine, D., Self-organization and dynamical transition in traffic-flow models, Physical Review A, 1992, 46 (10-15): 6124 – 6127.

[7] SUN Yu. Role of Arbuscular Mycorrhizal Fungi in Plant Ecosystems [J]. Heilongjiang Agricultural Science, 2011, (8): 128 - 131. DOI: 10. 3969/j.issn.1002-2767.2011.08.046.