Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
A		2106187

Predicting Growth of Fungi and Species Competitions under Different Environments Using CA Modeling

Summary

Decomposition of compound is an important part of carbon cycle while fungi plays a vital role in decomposing woody fibers. A fungus' **decomposition rate** can be affected by various external factors as well as its biological properties. In this paper, we mainly consider only two factors: **extension rate** and **moisture tolerance**. However, in order to simulate real conditions, we also need to consider the competition between fungi as well as the changing environment pattern. Thus, the method of mathematical modeling is applied to create a proper simulation and prediction of the growth of fungi under different conditions.

Firstly, in order to establish the whole model, **CA modeling** is used for the demonstration of fungi's growth. We **recalculated the decomposition rate** based on its relation with both **extension rate and moisture tolerance** using a **weight constant**. The ranking system for competition between fungi is modeled using **ELO system** which is mostly commonly used among chess players and is proved to be applicable to such bio-system. We assigned the rules for fungi to grow and compete and finish the whole set-up of the CA model. In order to make it closer to reality, we take into consideration the effect of **hypha thickness** which may affect the result of a competition and defined the calculation formula. Various **visualization** including mapping, line chart and surface chart are used for representation.

Secondly, we moved to adding environmental fluctuations and variation of annual weather pattern. Since fungi have temperature and moisture niche range in which they achieve fastest growth, we added the formula of **penalty term** to simulate the possible inhibiting effect. To explore how external temperature and moisture affect the competition as well as the growth of fungi, we selected **12 fungi species** to perform **2v2 competition** and compared two sets of results before and after adding annual patterns. Short and long term interaction are classified by years. Around one year is considered as short and a period of 10 years are regarded as long. For **stable conditions**, results can be categorized into **overwhelming winning-losing, quickly determined winning-losing, deuce at first, and long-run competition.** After **adding annual weather pattern**, we observed difference including: **the resulting curves are less smooth, the time consumed for winning competition is much longer, and there's even possible for a reversed ending.** We also tested fungi's stability under rapid and larger fluctuations, obtaining the result that **species with larger temperature and moisture niche width can be considered relatively stable**, which agree with the provided task article.

Thirdly, five different environments including tropical rain forest, arid, semi-arid, temperate and arboreal are tested one by one to find the advantage and disadvantage of each fungus. To make the result clearer, we continued to use the 12 species and **grouped and analyze them by the effect they experienced on the change of climate**. From the grouping, we tested **possible combinations** between species for all five environments that are possible to **persist for at least 10 years**. Detailed process of how to filtrate groups is presented using tropical rain forest as example.

Finally, we tested how **diversity** of species affect the decomposition of wood. By **controlling the total number** of fungi planted initially and **varying the species include**d, we concluded that t**he wood plate is consumed more** when the fungi planted on it is with **larger diversity**.

Fungi play a vital role in the process of decomposition, thus pushing the whole carbon cycle in ecological systems. It's important for us to learn more about the habitus of fungi, so we included a two-page article written in the style of college testbook as another form of summary of our work.

Key words: Fungi, CA modeling, Elo system, Species Interaction & Competition, Climate, Diversity

Contents

1 Introduction

1.1 Background

The carbon circle plays an important role in the operation of ecosystem on Earth. While plants transform the inorganic carbon in the environment into organics, there must be some other creatures transforming organics back. As the primary decomposers of ground litter and woody fibers in ecosystems, fungi are critical agents of the global carbon cycle [1]. According to an article of a recent research, there are some fungi traits influencing the decomposition rate, including the growth rate (described by the hyphal extension rate), and the moisture tolerance [1]. The traits vary between different species of fungi, and the research shows: those fungi with higher growth rate and competitiveness decompose materials faster; while the fungi which grow slower, with better adaptation to different moisture conditions, decompose the materials slower [1].

Figure 1: A mushroom (a type of fungi) decomposing the dead plant material [2].

1.2 Analysis & Problem Restatement

In this problem, we need build models to describe the decomposition process of ground litter and woody fibers in a certain area, with multiple species of fungi existing. Apart from the two traits of fungi, we also need to take the interaction of fungi species into consideration. When the environmental factors change, the growth rate of fungi, the interaction between species, as well as the decomposition rate will change. Hence, for this problem, the work to do includes:

1. For a certain amount of ground litter and woody fibers, build a mathematical model to relate the decomposition process with the traits (different growth rates and moisture tolerances) of different species of fungi there. Take the interaction of those multiple fungi species into account.
2. How do different species of fungi interact with each other? Analyze the trends of interactions in both the short-term case and the long-term case. In the analysis, the impacts of following environmental factors should be included: rapid fluctuations, changes of atmosphere trends (local whether pattens).
3. For five different environments (arid, semi-arid, temperate, arboreal, and tropical rain forests), analyze the relative advantages and disadvantages of different species of fungi, and predict which kinds of species combinations tend to exist persistently.
4. By considering the breakdown rate of ground litter, describe the impact of diversity of fungi on the efficiency of ecosystems. Predict the effect and significance of biodiversity on the diversity of local environments.

2 Model Preparation

2.1 Assumptions

In order to simplify the problem and extract an effective model for solving it, the following assumptions are made:

1. The decomposition rate is only influenced by two traits of the fungi: the **hyphal extension rate** and the **moisture tolerance**. Although other traits may also influence the decomposition rate, they are not the focus of this problem.

2. **The only decomposer** in this problem is the fungi. Other creatures (such as bacteria) will make **no** contribution to the decomposition processes.

3. We only consider the growth (namely the hyphal extension) of fungi, and **reproduction is excluded from the problem**. Besides, each unit piece of hyphal of the same fungus will decompose the material **at a constant rate** over time, as long as the environmental conditions do not change, until all the material it covers is decomposed.

4. The decomposition rates do **not** vary between different types of ground litter and woody fibers. In other words, all the material to be decomposed are **homogeneous**.

2.2 Notations

For clarity, the notations used for the models are listed in Table 1. **(Note: The * marked on the definitions indicates that the symbols represent quantities of a single species of fungus. Those quantities varies between different fungi species.)**

Table 1: Notations

Symbol	Definition	Unit
D	Decomposition Rate*	% (of mass)/122 day
D_1	The part of D determined by hyphal extension rate*	% (of mass)/122 day
D_2	The part of D determined by moisture tolerance*	% (of mass)/122 day
ω	The weight of D_1 in D	
E	Hyphal extension rate*	mm/day
E_0	Maximum extension rate at the optimal moisture*	mm/day
M_t	Moisture trade-off/ moisture tolerance*	
m_0	The optimal moisture*	
m	Moisture at the moment*	
T_0	The optimal temperature*	$^\circ C$
T	Temperature at the moment*	$^\circ C$
R	Competitiveness ranking of a fungus species*	
B	Moisture niche width (scaled to $[0,1]$)*	
L	Total length of the hypha*	mm
l_0	Initial length of the hypha*	mm
t	Elapsed time (from the beginning of decomposition)	day
x	Mass of material decomposed in one day*	g/(mm $\cdot$ day)
d	Thickness of hyphae	mm
λ	Winning coefficient of fungus ranking higher	

3 Model of Wood Breakdown by Multiple Fungi Species

3.1 Model Overview

In order to simulate the real process of fungi's growth, consumption, and competition, CA modeling is used to create a dynamic evolutionary process, making it more convenient to analyze. To drive the whole process, the model is divided into three parts:

1. Define and calculate the decomposition rate with respect to extension rate as well as moisture tolerance. At the same time, consider the effect moisture has on the extension rate.
2. Define the situation and solution when two fungi meet and compete using competitive rankings. Elo system is adapted which has been proved to be quite efficient [1].
3. Apply CA modeling to explicitly show the process of the wood occupation and interactions between fungi.

Then, various kinds of figures are used to demonstrate the result: 2D mappings used for showing the process of fungal growth, line charts for showing the variation of area occupation of multiple fungi, and surface plots used for reflecting the number of hyphae as well as the consumption of materials.

3.2 Calculating Decomposition Rate

The decomposition rate is related to both the extension rate (growth rate) and moisture tolerance. The extension rate can be affected by the species of fungi, fungi's moisture niche width, and the exact environmental moisture. Thus it can be obtained by Eqn. (1).

$$E = \begin{cases} E_0 & m \in [m_{min}, m_{max}] \\ E_0 \times e^{-min\{|m-m_{min}|,|m-m_{max}|\}} & m \notin [m_{min}, m_{max}] \end{cases} \tag{1}$$

The tolerance of moisture is defined to be the difference between fungal isolate's competitive ranking and moisture niche width, both scaled to [0,1].

$$M_t = R - B$$

Since the ranking data obtained from the article is already scaled among 34 different species [1], we modify each ranking by Eqn. (2) when the chosen species for the model is much smaller.

$$R_i' = \frac{R_i}{\sqrt{\sum_{i=1}^{n} R_i^2}} \tag{2}$$

where R_i denotes the i^{th} isolate among the n selected species.

The relation between both factors and the decomposition rate can be obtained from a research article by Lustenhouwer and other scientists [1], which is shown as the equation below.

$$\begin{cases} log(D) = 0.32log(E) + 12.48 \\ log(D) = 0.82M_t + 1.87 \end{cases} \rightarrow \begin{cases} D_1(E) = 12.48 \times E^{0.32} \\ D_2(M_t) = e^{0.82M_t+1.87} \end{cases}$$

Since above are the only two traits that are considered in affecting decomposition rate, we combine the two relationships using a weight constant:

$$D = \omega \times D_1 + (1-\omega) \times D_2 \tag{3}$$

However, the unit for extension rate is mm/day while the calculation for decomposition rate is the percentage mass loss over 122 days. Thus to simplify model calculation, we further derived the equation for calculating the mass consumption per day, by per unit length of one certain fungus. Using Eqn. (3), we then solve for x to get the assumption rate, which is described as grams of wood per day, considering the hyphal length growth of the fungi with respect to time.

$$
\begin{aligned}
L &= l_0 + Et \\
D &= \int_0^{122} Lx dt = \omega \times D_1 + (1-\omega) \times D_2
\end{aligned}
$$

3.3 Competition and Ranking

From Lustenhouwer's work, the condition for single fungus isolate consuming wood is already clear. However, the model needs to describe and predict the decomposition and living condition when multiple fungi species are present. Thus we need to determine a rule for competitions between different species when they meet each other. The moisture tolerance includes an interesting factor called competitive ranking, which is exactly what we need.

The competitive ranking reflects the ability for a fungus to out-compete other fungi in pairwise testing under the same condition [4]. The ranking is tested in reality and calculated following the Elo ranking system which is commonly used among chess players. According to the Elo ranking system, the score is calculated based on all previous competition results and can be used to predict future odds of players [5]. Also, each competition affects the involved players. The prediction and the modification of ranking formula can also be directly applied to the ecosystem with a simple change of parameter K.

$$
\begin{cases}
P_A = \dfrac{1}{1+10^{(R_B-R_A)/k}} \\
P_B = \dfrac{1}{1+10^{(R_A-R_B)/k}}
\end{cases}
\qquad
\begin{cases}
R_A' = R_A + K(S_A - P_A) \\
R_B' = R_B + K(S_B - P_B)
\end{cases}
\tag{4}
$$

where E_A and E_B reflects the possibility of each player to win, while R_A and R_B denote their competitive rankings. k is the constant found especially for the fungi ecosystem. R_A' and R_B' are the modified rankings after each competition.

3.4 Predicting the Breakdown Process Using CA Modeling

In order to demonstrate the growth and competition among multiple fungi species, we adopt the cellular automata modeling as the main model structure. Cellular automata is a model that defines **a finite space** and a series of **discrete cells**. These cells will automatically evolve according to the different states of their eight **neighbors** and follow certain **evolution rules**. It is a dynamic and discrete system which can simulate the growth, decomposition, and competition of various fungi on the wood very well. Fig. 2 shows a brief sketch of cellular automata model.

Fig. 3 is the **evolution rules** for a fungal cell. In the whole process, the growth speed of the cell follows the modified extension rate which is shown on Eqn.(1). The winning probability is defined by Elo rating system which is shown on Eqn.(4) and the decomposition rate is calculated by Eqn.(3).

Since the data for extension rate we obtained is corrected to two decimal places, we define a wood plate with the same area of the CA model as the land for growing fungi, and assume that the wood is abundant enough during the time period of the whole prediction process (which means the wood will not be completely consumed). Thus we define the size of our CA model to be a **300 × 300 map** with each cell having a side length of 0.01 mm for the demonstrations.

For each single cell, there are properties including the original mass of materials W per cell, the total length of hyphae in a single cell, the current remaining mass of materials, and the name of the

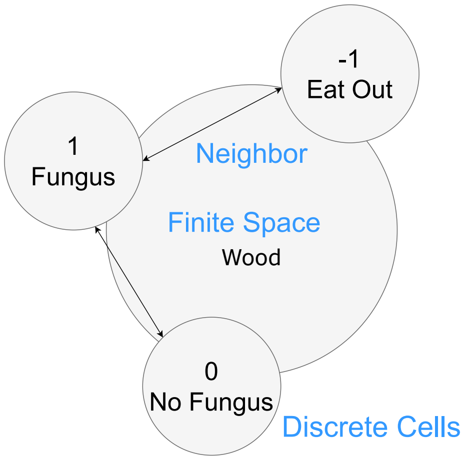


Figure 2: Cellular automata model.

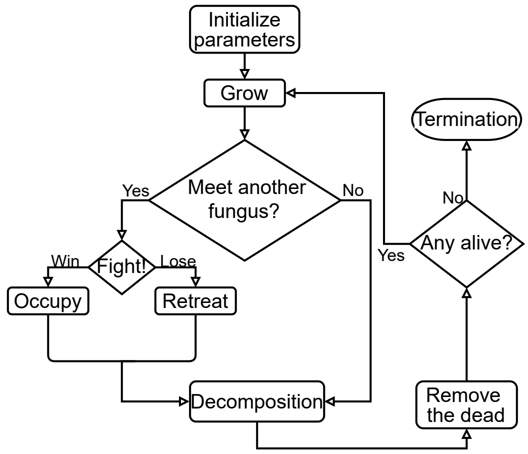


Figure 3: Algorithm schematic.

fungus occupying it. According to CA modeling, the condition of each cell may be affected by adjacent cells. Thus, the growth of the fungus is defined to be extending both vertically and horizontally. Each time when the fungus occupies a new cell, it will start growing from the new cell as well on the next day. An explicit demonstration is shown in Fig. 4 where we assume the fungi grow 0.01 mm longer each day.

When two different fungi meet each other during their growth, competition occurs to judge which one takes up the cell. Since the extension rate of different fungi are not the same, we assume competition only happens at the cell when the two fungi meet and will not affect those cells that have not been occupied. Fig. 5 demonstrates the condition. It is clear that once two fungi start competing, the competition will not end immediately since adjacent cells are always occupied by either fungus.

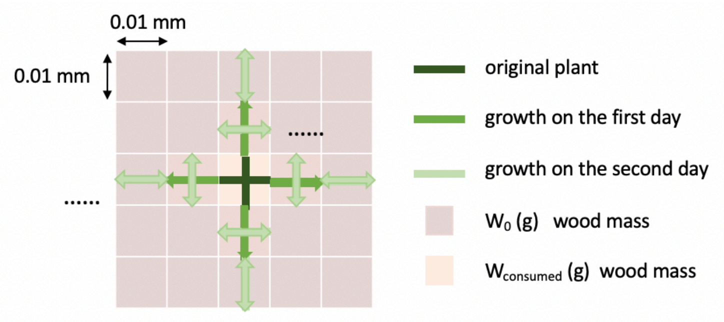


Figure 4: Demonstration of the growth modeling (assume the fungi grow 0.01mm longer each day).

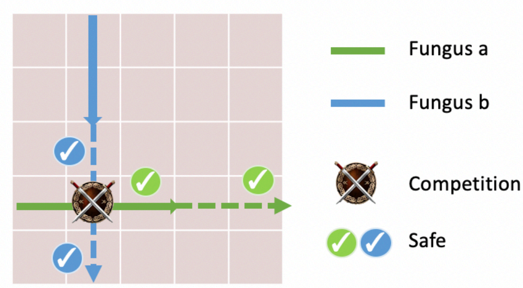


Figure 5: Demonstration of the competition (one fungus grow into a cell taken up by the other).

Finally, since the materials are limited and we first take the material's reproduction out of consideration, when the fungus consumes all materials in a certain cell, the cell will be changed to death and all the hyphae in this cell also die immediately. Once a cell is dead, no more fungi can ever come in and occupy it, no matter how they grows.

3.5 The Effect of Hypha Thickness in Interactions

Based on the work above, we are now going to make an improvement on the model of interactions between fungi. In the above parts, results of competitions are only influenced by rankings and extension rates of fungi. Therefore, if the ranking of a fungus (called fungus A) is much higher than the other one (fungus B), it will be very likely to occupy nearly all the area that fungus B owns. However, there should be a balance in the real case. Consider that the fungus B starts growing at a point (called the initial point). As time goes on, there should be more hyphae around the initial point of fungus B than at the edge of extension of fungus A. In other words, hyphae on the area around initial point of growing are thicker, thus more difficult to be replaced by other species. As a result, uncompetitive fungi tend to grow persistently in a small area, even though they are surrounded by competitive fungi.

$$\lambda = \frac{2}{1 + 3e^{-\ln 3y}} \quad (y > 0)$$

$$y = f(d, \frac{R_A}{R_B}) = \begin{cases} e^{-k_1 d} & \frac{R_A}{R_B} > 1 \\ \ln(k_2 d + e) & \frac{R_A}{R_B} < 1 \end{cases}$$

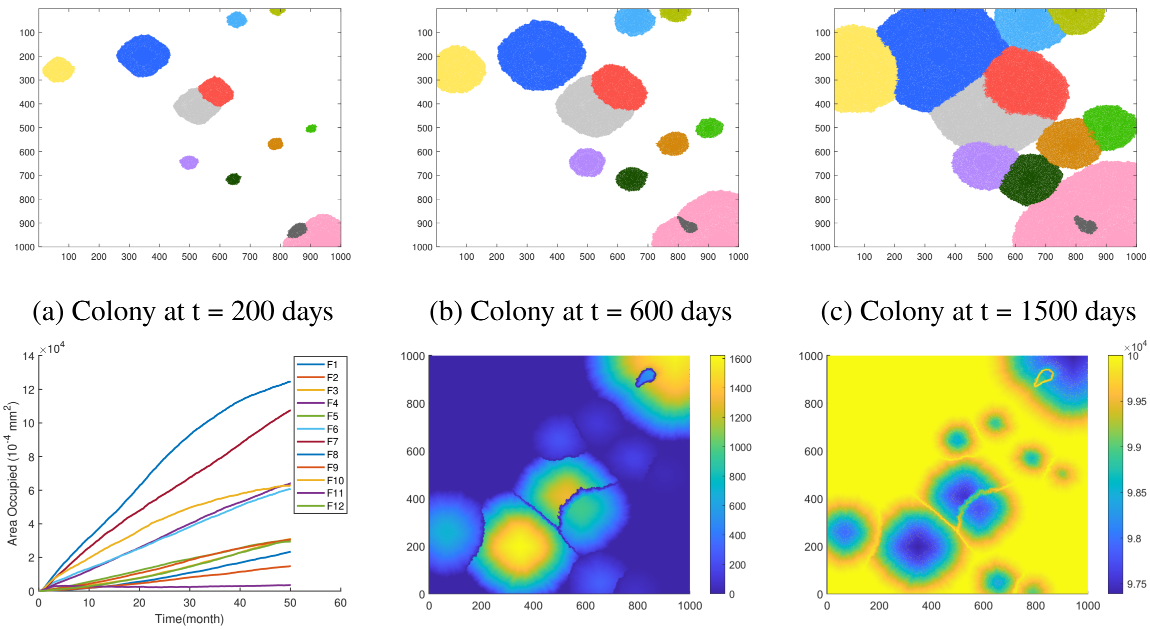
As shown in the above equations, we introduce two new quantities d and λ. d is the hyphal thickness of the fungus B (the fungus being attacked), and λ is the winning coefficient, in the form of a Logistic function. The larger λ is, the higher probability that fungus A will take over the cell. R_A and R_B are the rankings of fungi A and B, respectively. In this example, $\frac{R_A}{R_B}$ is greater than 1. If $\frac{R_A}{R_B}$ is smaller than 1, namely fungus B is more competitive than A, the equations can still be applied. For the case of $R_A = R_B$, we quantify the effect of d by $\Delta(d)$, as shown in Eqn. (5). With λ and $\Delta(d)$, The expressions of fungi A's and B's opportunities to win are modified into Eqn. (6).

$$\Delta(d) = \begin{cases} k_3 \ln(\frac{x}{l_0} + 1) & R_A = R_B \\ 0 & R_A \neq R_B \end{cases} \tag{5}$$

$$E_A = \frac{1}{1 + 10^{\lambda(R_B - R_A)}} - \Delta(d), \quad E_B = \frac{1}{1 + 10^{\lambda(R_A - R_B)}} + \Delta(d) \tag{6}$$

3.6 Visualization

In order to demonstrate the process of fungi's growth as well as their properties including occupied area, total hyphal length and their consumption of wood materials, we made the following visualization including mappings, line charts and surface plotting. Fig. 6a to Fig. 6c shows their movement and extension, while Fig. 6d to Fig. 6f reflects the three properties just mentioned.



(a) Colony at t = 200 days (b) Colony at t = 600 days (c) Colony at t = 1500 days

(d) Area occupied (e) Hyphal thickness (f) Thickness of wood left

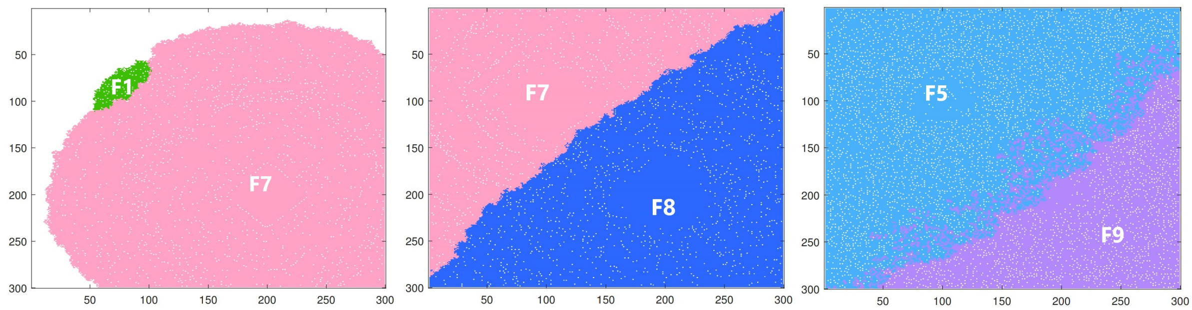
Figure 6: The decomposition process and results ((c), (d), (e)) at the 1500th day.

4 Analysis of Interactions

4.1 Fungi's Interactions without Environmental Changes

Before considering the environmental factors, the model is first used to predict the interaction between two fungi under a relatively stable condition. A total of 12 species named F1 to F12 is chosen for testing with data obtained from Maynard's work on Nature [3] and the results are concluded into short-term trends and long-term trends. The conclusion is used as a reference and comparison for the next part.

The conditions for *2 vs 2* competition can be categorized into four types as follows. In each category, we choose a typical example for demonstration. (Note: Each pair is denoted as the combination of two names. For example, pair "F1F7" means the interaction between F1 and F7. "Boundary" means the line where the two colony meets.)

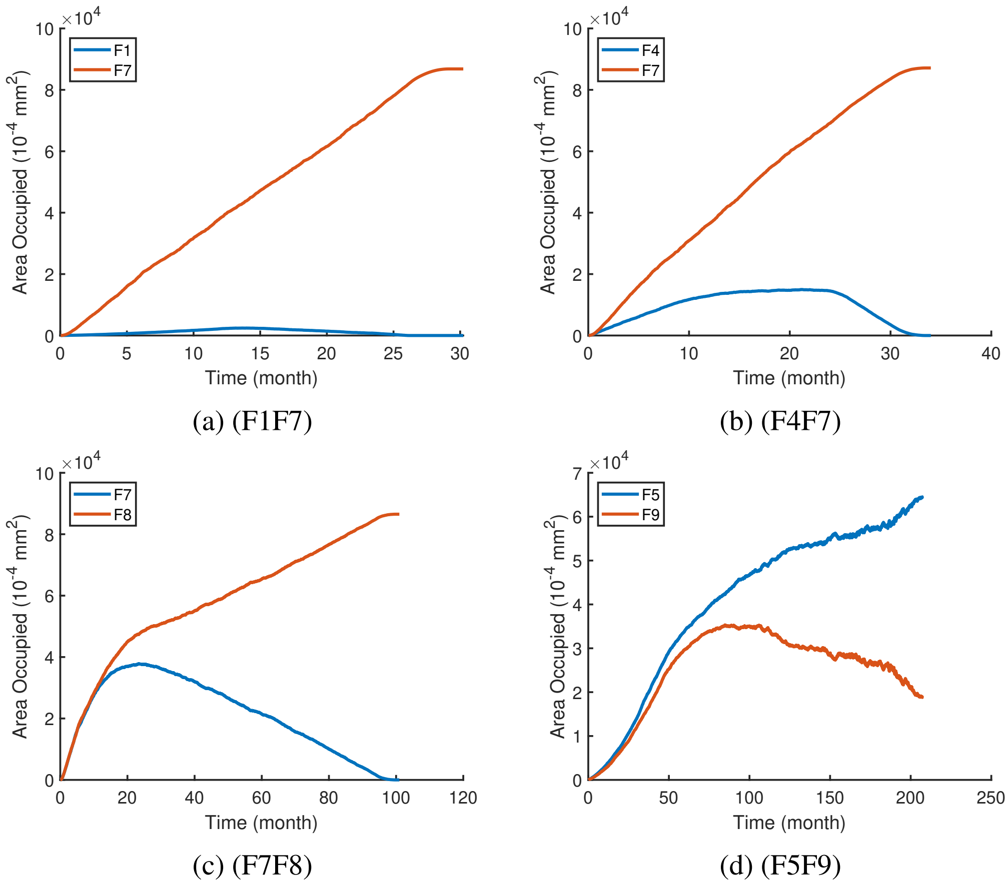


(a) Colony of F1F7 (Day 650) (b) Colony of F7F8 (Day 860) (c) Colony of F5F9 (Day 4500)

Figure 7: Colony of fungi (without environmental changes).

1. **Overwhelming winning-losing** (Pair: F1F7; $E_7 >> E_1$, $R_7 >> R_1$)
   Short-term: F7 grows much faster than F1. As they meet, their boundary moves quickly towards F1 without deadlock, as shown in Fig. 7a.
   Long-term: F7 coves F1 totally and occupies the whole area.
2. **Quickly determined winning-losing** (Pair: F4F7; $E_7 > E_4$, $R_7 > R_4$)
   Short-term: F7 grows faster than F4. Some degrees of deadlock at the boundary.
   Long-term: Winning-losing is quickly determined and F4 is driven out.
3. **Deuce at first** (Pair: F7F8; $E_8 \approx E_7$, $R_8 > R_7$)
   Short-term: The boundary is formed at the diagonal as shown in Fig. 7b. No obvious trend of winning-losing.
   Long-term: F8 gradually drives out F7, with a clear boundary in the process.
4. **Long-run Competition** (Pair: F5F9; $E_5 \approx E_9$, $R_5 \approx R_9$)
   Short-term: The boundary is formed at the diagonal. No obvious trend of winning-losing.
   Long-term: The competition lasts for a very long time and F5 previals slowly. There is obvious a deadlock at the boundary, as shown in Fig. 7c.

The following four figures are the plots of areas occupied by each fungus with respect to time, which reflects the four conditions mentioned above.



(a) (F1F7) (b) (F4F7)

(c) (F7F8) (d) (F5F9)

Figure 8: Area occupied by fungi in different interactions (without environmental changes).

4.2 Changing Atmospheric Conditions: Temperature and Moisture

To analyze the trends of interaction in a long time, the changing of environmental conditions must be taken into consideration. To simulate the changing of weather patterns in a year, we find the data of monthly temperature and precipitation in Boston in 2020, as shown in Fig. 9 [6].

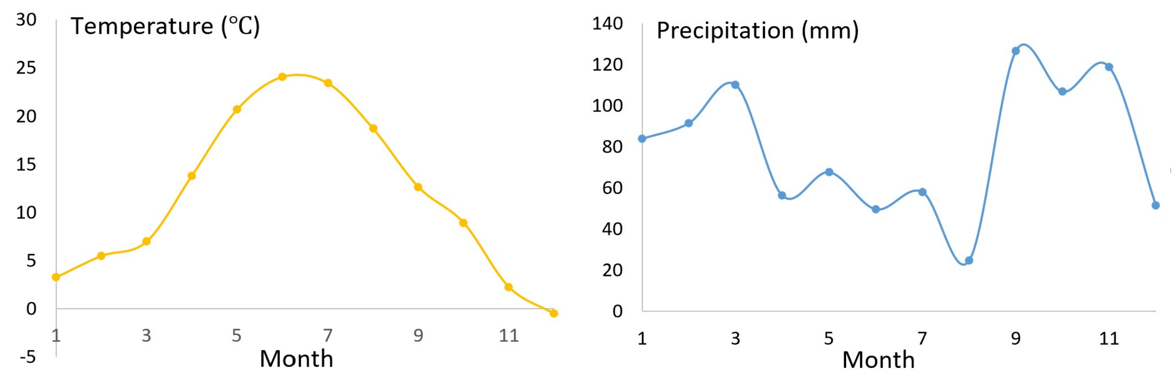


Figure 9: Monthly Average Temperature and Precipitation in Boston, 2020 [6].

We approximate the moisture by scaling the precipitations into values between 0.08 and 5.25, because no direct information of moisture is found and the trends of moisture and precipitation should be very close to each other, according to literature [11]. Then we fit the data into functions, as the expressions of temperature T and moisture m. Eqn. (7) is the temperature function of time t (the moisture function is more complicated and not listed here).

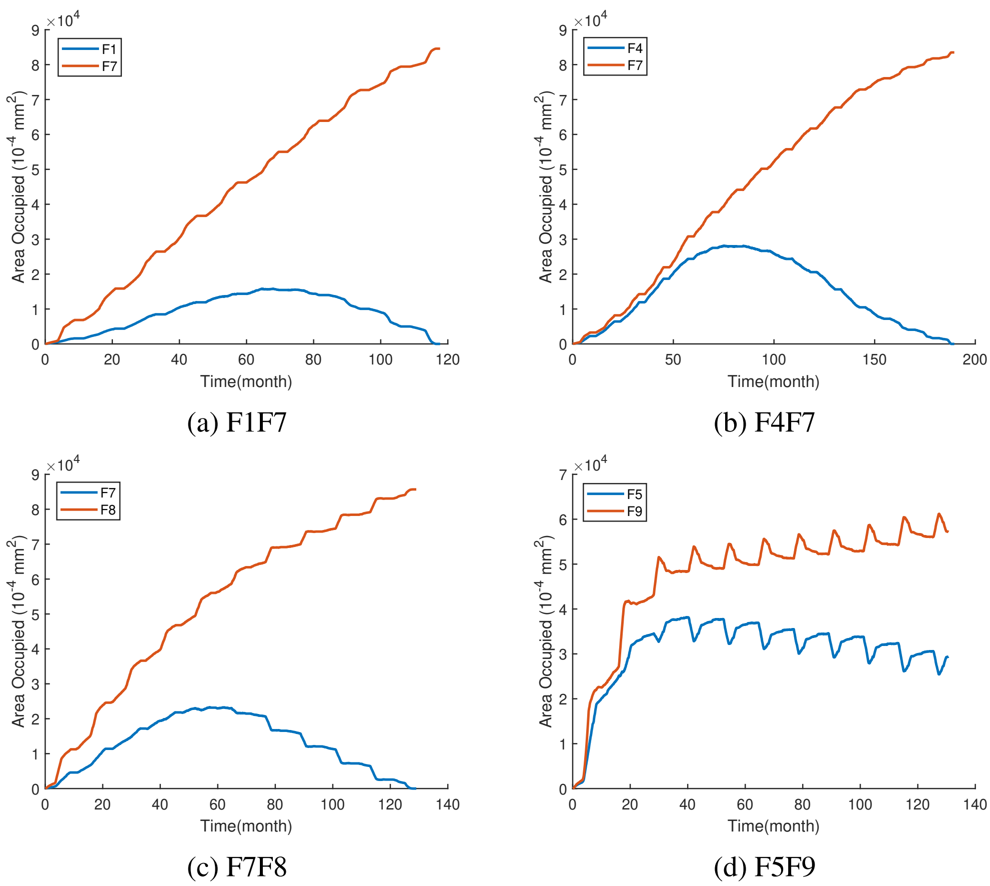
$$T = 12.3\cos(\frac{2\pi}{365}t - \frac{\pi}{2}) + 11.75 \tag{7}$$

If we denote $[m_{min}, m_{max}]$ as I_m and $[T_{min}, T_{max}]$ as I_T, the expression of hyphal extension rate now becomes:

$$E = \begin{cases} E_0 & m \in I_m, T \in I_T \\ E_0 \times e^{-\min\{|m-m_{min}|,|m-m_{max}|\}} & m \notin I_m, T \in I_T \\ E_0 \times e^{-0.1\min\{|T-T_{min}|,|T-T_{max}|\}} & m \in I_m, T \notin I_T \\ E_0 \times e^{-\min\{|m-m_{min}|,|m-m_{max}|\}} \times e^{-0.1\min\{|T-T_{min}|,|T-T_{max}|\}} & m \notin I_m, T \notin I_T \end{cases}$$

4.3 Interactions between Fungi with Environmental Changes

In order to show how the environmental conditions influence the interactions of fungi, we choose the same four pairs of fungi as in Section 4.1 for analysis. The area-time plots are shown in Fig. 10. Comparing with Fig. 8, the interactions with environmental changes show some different trends, which are going to be discussed next.

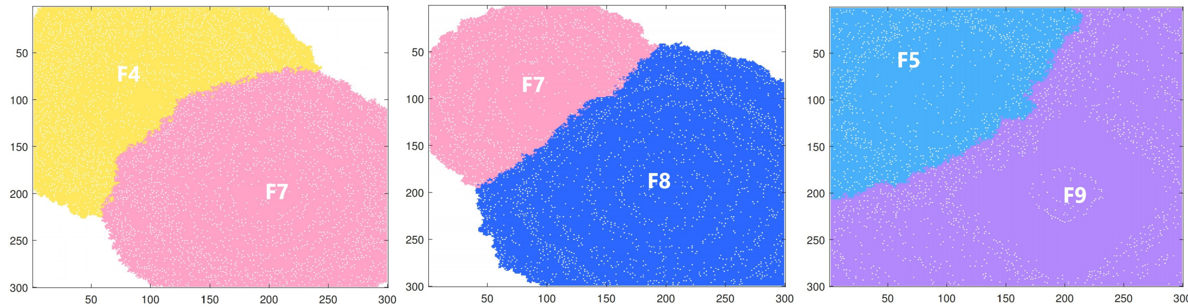


(a) F1F7 (b) F4F7

(c) F7F8 (d) F5F9

Figure 10: Area occupied by fungi in interactions (with atmosphere trends changing).

Firstly, the area-time curves in Fig. 10 are **no longer as smooth as** in Fig. 8. Instead, there are periodical dentate fluctuations on the curves. This is a result of the changing temperature and moisture in each year. Another phenomenon reflecting the annual changes is the "growth rings" on the colonies, as shown in Fig. 11 (especially on the colony of F8). When the temperature and moisture are suitable, the fungi grow faster and the hyphae look sparser; and when the conditions are unsuitable, the hyphae look denser.



(a) Colony of F4F7 (Day 2500) (b) Colony of F7F8 (Day 1550) (c) Colony of F5F9 (Day 3920)

Figure 11: Colony of fungi (with atmosphere trends changing).

Secondly, the **"overwhelming winning-losing" condition disappears**. In pair F1F7, the weaker fungus F7 exists for a longer time than before, and the maximum area it occupies also increases. The similar thing also happens to F4F7. The explanation is, the preponderance of F7 is weaken when the environment is changing because of its low tolerance to different temperature and moisture conditions.

Thirdly, **the competition result in a pair can even be reversed**. Comparing Fig. 10d with Fig. 8d, and Fig. 11c with Fig. 7c, we can see that the previaling fungus turns from F5 to F9. This is because F9 can adapt the temperature changes better. Besides, the competition between F5 and F9 becomes a "seesaw battle" when the environmental conditions change regularly.

Another thing to notice is that, in Fig. 11, the **orientations of boundaries are different**. The orientation of boundaries reflects the relative preponderance of competitiveness and growth rate. For example, in Fig. 11a, the boundary bulges to F4, which is in the direction of its movement. This indicates that F7 wins F4 mainly by high competitiveness (ranking). In Fig. 11c, the boundary is concave with respect to its moving direction, which indicates that F9 wins F5 mainly by high growth rate.

4.4 Impact of Rapid Fluctuations in External Environment

In order to study the impact of rapid environmental fluctuations on the interaction of fungi, we firstly simulate an environment with fluctuating temperature and moisture, as shown in Fig. 12. The fluctuations are created by randomizing the values every five days.

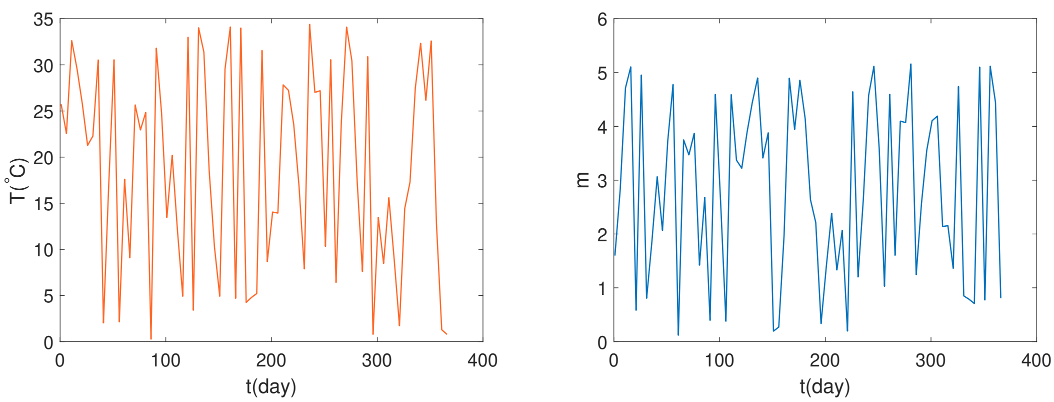


Figure 12: Patterns of rapid fluctuations in temperature T and moisture m.

Then the celluar automata model will be used to simulate how a single fungus grow under random and rapid environmental changes. Documentation claims that the hyphae of fungi that can better adapt to the environment are denser and expand more slowly [1], so will they have high adaptability in this random environment? We mainly measure the change of the surface area of a fungus on 100 [mm] × 100 [mm] wood blocks. It will expand from the center until covering the whole block. Fig.(13) shows the process and area occupation curve for 12 different fungi under 5 different random conditions.

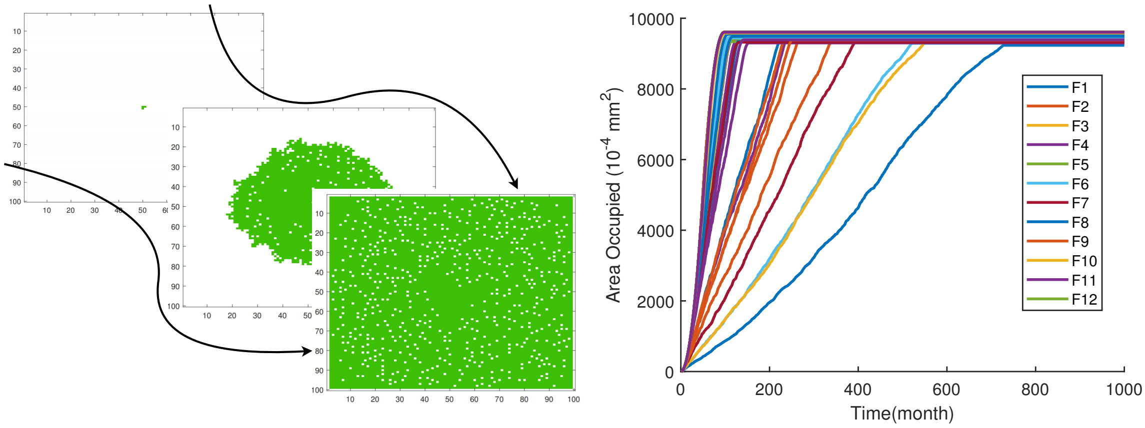


Figure 13: Testing process and results for rapid fluctuations in T and m.

From the Fig.(13), we can find that some color curve families, such as F3-orange curve family, do not deviate too much from each other and almost grow in the same trend, while some color curve families, such as blue-F8 curve family, deviate much from each other. This is because fungi like F3 have a higher moisture niche width and temperature niche width. When they face the fluctuation of the environment, their range of change is smaller which means that they are more **stable**.

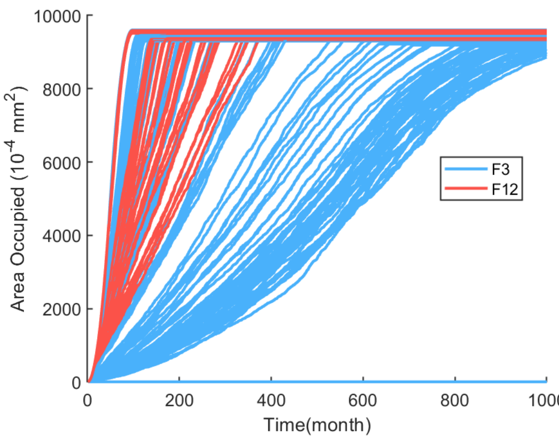


Figure 14: Area change curves of F3 and F12 (50 for each).

Also, this kind of stability will also affect the speed of expension. For example, the expension speed of F12 fungi is 0.77 mm/day while the expension speed of F3 is greater than F12 which is 1.09 mm/day. However on Fig.(14), we repeat the simulation 50 times for F3 and F12 and conclude that the average expansion speed of F12 is much higher than F3. This means that those kind of fungi that are more stable will also have **advantage on expansion speed** when facing great environmental changes.

5 Fungi Communities in Different Environments

In this part, predictions about the relative advantages and disadvantages for each species and combinations of species likely to persist are made using the previous designed model. Fig. 15 shows the temperature and precipitation of five different climates under which we tested the vitality of our fungi. In order to select the best combinations, we have come up with one efficient way after real testing. One detailed example (tropical rain forest) is written down to demonstrate the process and the other four are only presented with a summarized result including advantages and disadvantages for each fungus as well as some possible combinations due to the page limit.

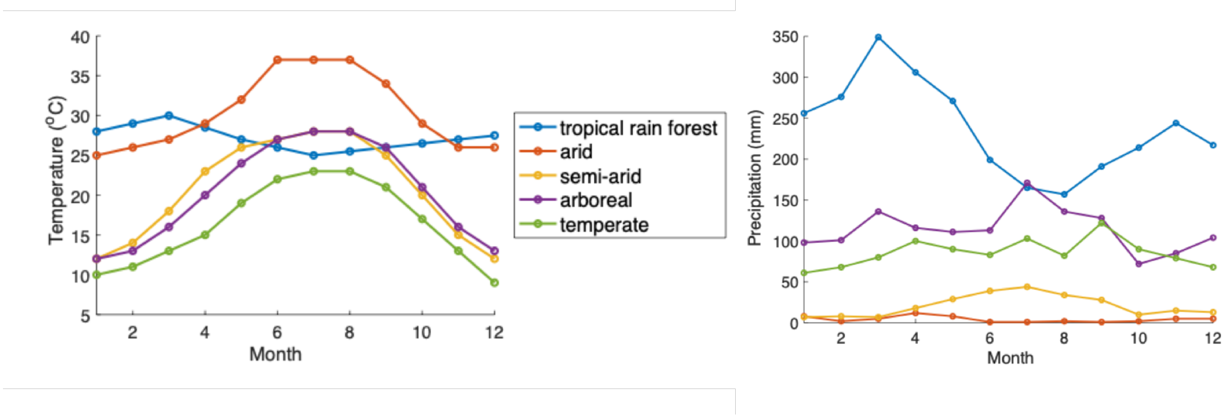


Figure 15: Temperature and precipitation of five climates. [7, 8, 9, 10]

5.1 Example: Tropical Rain Forest

Tropical rain forest climate has a relatively high temperature of 25-30°C and a precipitation of >200 mm per month throughout the whole year. Thus, we first test the yearly performance of each fungus's growth. In order to first let them grow freely with less interaction between species, the testing is broken down into three groups: F1-F5, F6 & F9-F12, F7 & F8, due to the fast growth of F7 and F8.The result is shown in Fig. 16 to Fig. 18.

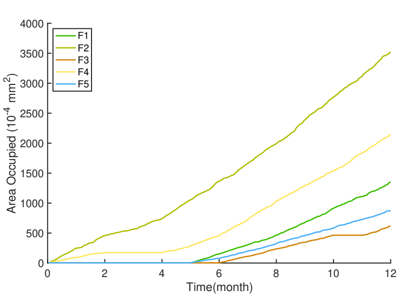


Figure 16: Yearly growth of F1-5.

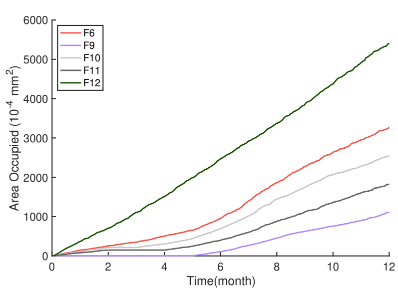


Figure 17: Yearly growth of F6,9-12.

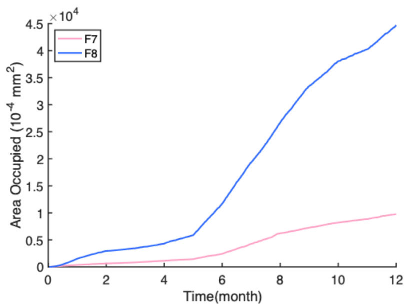


Figure 18: Yearly growth of F7 & 8.

Then we can conclude the effect of annual temperature and precipitation changes on all 12 fungi and analyze their advantages and disadvantages according to the similarity of their area-time curves.

1. **F6, F7 and F8: Partially affected for 6 month**
   These four fungi grow continuously throughout the whole year. During month 5-10, the external environment lies well in their temperature and moisture width, thus achieving fastest growth. During the other 6 month, although growth slows down due to relatively less precipitation, they encountered no great damage for normal extension. All four fungi have high extension rates and rankings, ensuring them to still grow stronger.

2. **F1, F5 and F9: Partially hold-up for 6 month**
   The line chart for F1,5,9 shows that they experienced a stage of 6 month (1-6) when they can not grow successfully due to the high precipitation that is out of their moisture niche width. But

they can still grow normally during month 7-12 and show relatively good increase. The four have smaller extension rates and medium rankings, thus they can still grow quite well under safer conditions without some much stronger fungi competitors.

3. **F2 and F12: Most stable**
   These two fungi are not affected during the whole year of tropical weather. They demonstrated normal and stable growth, thus is the best species for tropical rain forest. While their extension rates and rankings are only medium, they still have competitiveness with those stronger but are more affected by the weather change.
4. **F4, F10 and F11: Minor hold-up for 2 month**
   F4 and F11 experienced no growth during month 2-4, but in comparison is still stable enough to grow under safe conditions. They have higher extension rates, but F11 has a much higher ranking than F4. Thus F11 may have better competitiveness to live with stronger fungi.
5. **F3: Almost hold-up for 8 month.**
   F3 can only grow normal during 4 month in tropical weather. Since it also has a ranking of 0, under most condition it can not grow successfully.

Here it is important to mention: since the properties of 12 fungi are already quite different, thus we focus more on the **effect exerted by the external environment** (which means the change of the curve trend) instead of simply comparing the area they occupied.

Then, we start to select possible combinations first from the same group, and then from cross groups, and finally with all fungi present. However, fungus **F8 shows absolute predominance** during testing, thus it is isolated and **removed** from the group testing from now on **under this climate**. Fig.19 to Fig.21 shows the result where we can find possible combinations after testing. Combinations of **F5 & F9, F6 & F12** and **F6 & F7** is possible to grow better together.

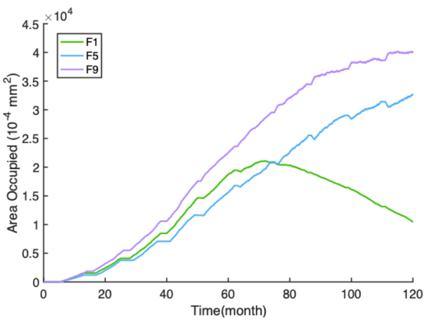


Figure 19: F1,F5,F9.

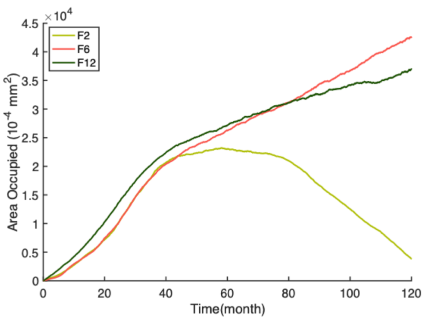


Figure 20: F2,F6,F12.

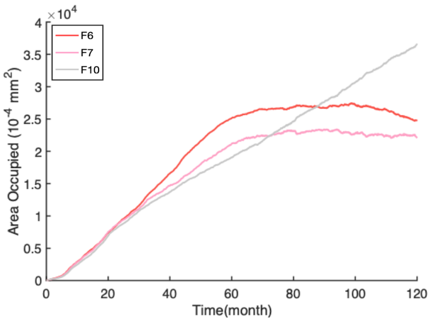


Figure 21: F6,F7,F10.

Finally, we test the condition of all 11 fungi (except F8) and conclude that **F7 & F10** achieves the best, with **F4, F6, F9, F11, F12** following and can still live and grow for a certain amount (although being restrained). The result can also be obtained from Fig. 31 to Fig. 33. Thus, the conclusion for the combinations under tropical rain forest is:

1. **Possible pairs: F5 & F9, F6 & F12, F6 & F7**
2. **Possible groups: F4, F6, F9, F11, F12 and F4, F6, F7, F9, F10, F11, F12**

One thing to mention is that: **pairs selected from one group may not be able to persist well**, since the groups form a certain balance between species to ensure their persistence.

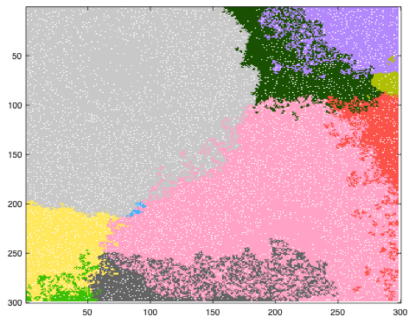


Figure 22: Ending condition.

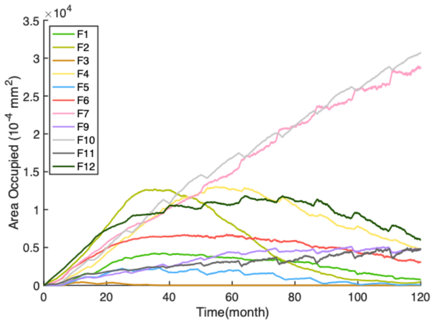


Figure 23: Curves in 10 years.

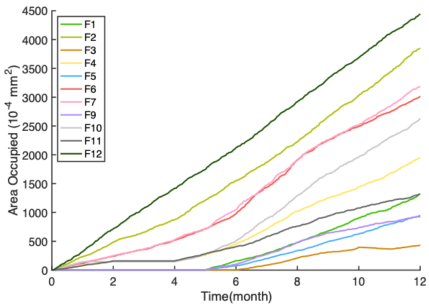


Figure 24: Yearly change.

5.2 Arid Climate

Arid climate is famous for annually high temperature and low precipitation, thus creating a great challenge for fungi's growth. The list below summarizes all the properties of 12 fungi under arid climate which is concluded from their annual growth behavior (which can also be partially reflected in Fig. 26).

1. **F4, F6, F7, F8, F10, F11: Partially affected of around 7 month**
   During roughly month 5-10, their growth slows down due to high temperature and almost no precipitation. During month 1, their growth slows down due to low precipitation. For the other time, they can still grow normally, but overall their extension speed is much lower because of low precipitation.
2. **F5: Most stable**
   According to its curve, F5 is not so affected by the annual weather change, thus it is the relatively stable one. But due to the severe environment, its growth still slows down to some extent.
3. **F2, F9, F12: Partially hold-up**
   During month 4-9, they all experience a stop in growth due to bad climate condition. Since they have relatively close extension rates, they may exist better with each other. However, they have much less competitiveness among other stronger fungi.
4. **F3: Minor hold-up of 3 month**
   F3 experienced no growth during month 6-8 due to the high temperature as well as low precipitation. Its growth in other time is partially reduced but it can still maintain normal living.
5. **F1: Comeplete dead**
   F1 itself is not a strong fungus. Under such bad condition, we can not observe any evident growth.

The result of the testing for the condition with all 12 fungi is shown in Fig. 25 to Fig. 27. We conclude that **F7 & F10** achieves the best, with **F4, F6, F9, F11, F12** following and can still live and grow for a certain amount (although being restrained).

Then, pairs and groups are found from the above division as well as the groups whose occupied area curve is closer to each other and tried one by one for testing. Below listed all the successful ones we found that can persist in a longer time period of ten years.

1. **Pairs: F4 & F7, F8 & F10, F2 & F3, F8 & F11, F9 & F12**
2. **Groups: F4, F5, F12 and F4, F6, F7, F8, F10**

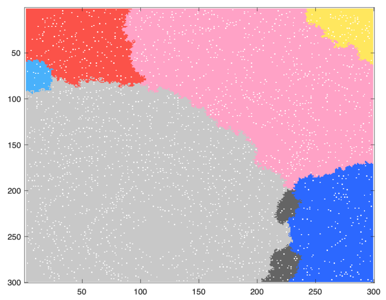


Figure 25: Ending condition.

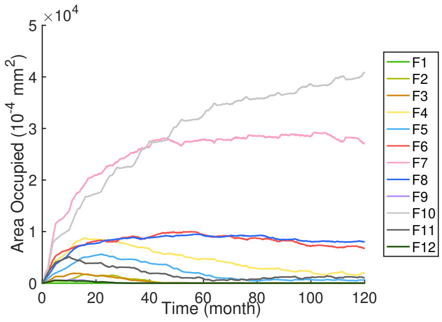


Figure 26: Curves in 10 years.

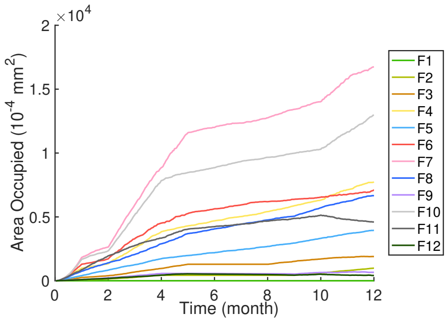


Figure 27: Yearly change.

5.3 Semi-arid

Semi-arid is also a tough climate, although slightly better than arid. It has a normal temperature curve but still lack of precipitation (<50 mm). However, the fungi seems to adapt best to such kind of environment. which can be seen from the advantage below that 8 can be categorized into stable. The conclusion of the advantage and disadvantage of all 12 fungi are listed below.

1. **F1, F2, F3, F4, F5, F9, F11, F12: Most stable**
   All the six species can grow well under semi-arid climate. The effect of environmental change on their annual growth is not obvious and they can easily achieve a stable growth.
2. **F6, F7, F8, F10: Partially affected for 5 month**
   During month 3-9 when temperature is relatively higher and there is some precipitation every day, the four species can achieve fastest growth. While in the other 5 month, their growth is reduced. Overall, they can still achieve a good extension thanks to their relatively higher extension rate.

The result of the condition with all 12 fungi is shown in Fig.28 to Fig. 30 and we conclude that **F7 & F8 & F10** achieves the best, with **F1, F4, F5, F6, F9, F11** following and can still grow for a certain amount (although being restrained).

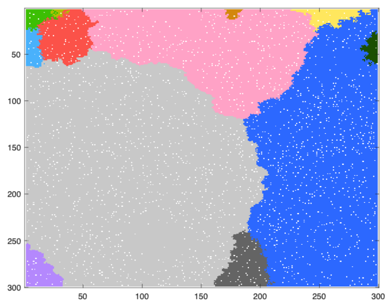


Figure 28: Ending condition.

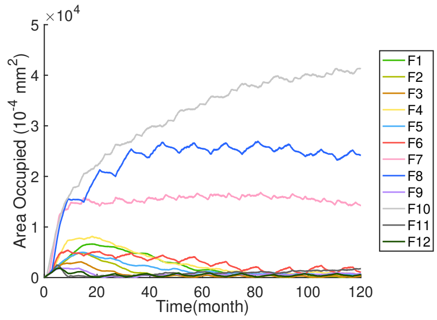


Figure 29: Curves in 10 years.

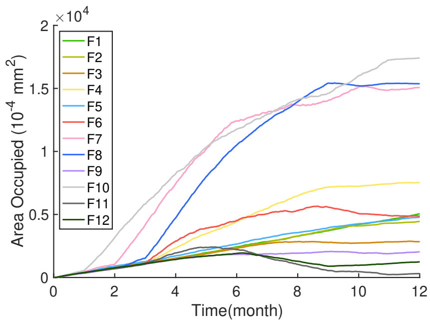


Figure 30: Yearly change.

After enough testing, we have found some combinations that can persist under semi-arid, that is:

1. **Pairs: F7 & F8, F4 & F6**
2. **Groups: F4, F5, F6, F9 and F5, F9, F12 and F7 & F8 & F10**

5.4 Temperate

Temeperate weather is the coldest one among the five we have chosen with the warmest month less than 25 degrees and a medium precipitation of 50-100 mm. The city Boston we have tested in previous section is also included in this type of environment.

1. **F1, F2, F3, F5, F9, F11, F12: Most stable**
   Temperate is also a good climate condition for these fungi, since their annual growth is stable and through the area they have occupied we can conclude that their extension rate is also not largely affected. This means the weather lies mostly in their niche width for temperature and moisture.
2. **F4, F10: Largely affected**
   There is only 2 month (7-8) when the growth of the two species is not reduced due to the relatively lower temperature that is not nice for F4 and 10. In other time period, their growth rate is sharply reduced which then makes them less competitive.
3. **F6: Minor affected for 2 month**
   The condition for F6 is just the opposite as the previous set due to its temperature niche width. Thus F6 can achieve much better annual growth under such condition and easily catch up.
4. **F8: Partially affected for 4 month**
   During winter, the growth of F7 decrease because of the low temperature. However, due to its high extension rate, such negative effect is not so dangerous for it to live on.
5. **F8: Fluctuation**
   F8 is the only interesting phenomenon that is observed. During summer time, its growth may experience a clear fluctuation. Its growth rate may be reduced every month after another. This somehow slow down its annual average growth. But it can still make up by its relatively high extension rate.

The result of the condition with all 12 fungi is shown in Fig.31 to Fig. 33 and we conclude that **F8**achieves the best, with **F8, F10** following and then **F1, F4, F5, F6, F9, F11** that can still grow for a certain amount (although being restrained).

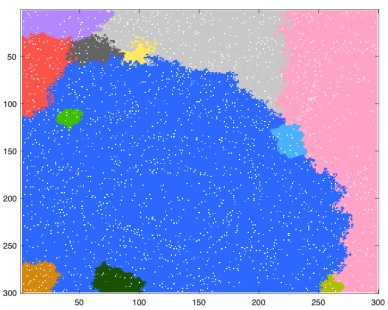


Figure 31: Ending condition.

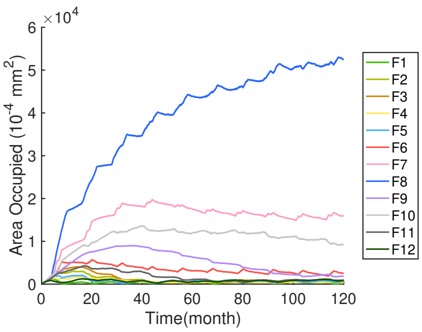


Figure 32: Curves in 10 years.

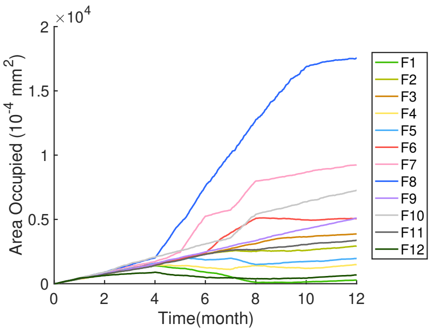


Figure 33: Yearly change.

Possible combinations for temperate climates includes:

1. **Pairs: F5 & F9, F6 & F7, F6 & F11, F7 & F8**
2. **Groups: F5, F6, F9, F11**

Compare with parts of the result obtained in previous parts, we can see that the pair "F5 & F9" appears again, which shows some degree of reliability of our model.

5.5 Arboreal

Arboreal is a relatively nicer climate for human as well as for fungi with 6 species being stable enough to external weather fluctuations. Luckily, it's also the second climate which is suitable for fungus F8 and it can eat up any other species along with it. Thus, from now on in this subsection, we **remove F8 temporarily** when testing.

1. **F1, F2, F3, F5, F9, F12: Most stable**
   With no danger around, their growth curves are highly slmilar and stable all year round. Comparing the area occupied, we can also see a slight increase which means arboreal is better for them to live.
2. **F4, F7, F10: Largely affected**
   For these three species, they only grow at fastest condition during month 9-10. In other time period, they growth rate is sharply declined.
3. **F8: Minor affected for around 3 month**
   During winter F8 is afffected by the low temperature which limits its growth. But in the other time since F8 has a high extension rate, it can soon catch up.
4. **F6: Partially affected for 6 month**
   In summer due to the slightly higher temperature, the growth rate of F6 is reduced. It is a disadvantage for it when other fungi are possibly at their best conditon.

The result of the condition with all 12 fungi is shown in Fig. 34 to Fig. 36 and we conclude that **F9, F10, F11** achieves the best, with **F1, F2, F4, F5, F6, F12** that can still grow for a certain amount (although being restrained).

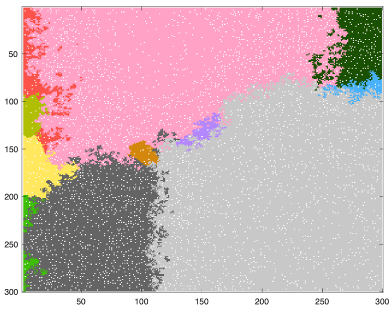


Figure 34: Ending condition.

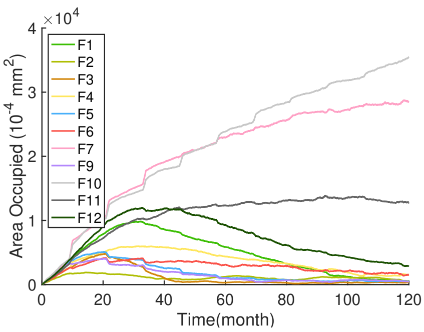


Figure 35: Curves in 10 years.

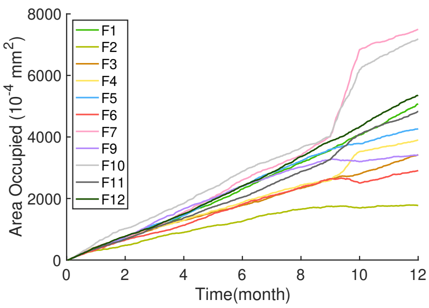


Figure 36: Yearly change.

For the final environment arboreal, the possible "partners" are listed as follows:

1. **Pairs: F1 & F4**
2. **Groups: F9, F10, F11 and F1, F4, F5, F6, F9**

6 Importance of Biodiversity

As introduced in Section 1, the breakdown of ground litter is an important process in ecological cycles. Therefore, the efficiency of decomposition is one of the determinants of the efficiency of ecosystems. In order to study the importance of species diversity of fungi, we are going to test whether the diversity of species will improve the efficiency of decomposition and adaptation to variable environments.

6.1 Fungi Combination Selection

First of all, according to the results of the previous models, we can get the following rules on the selection of fungi.

- According to the analysis of section 3 and 4.2, we need to choose species that can coexist peacefully on long-term trends to ensure the **stability of biodiversity**.

- From section 4.4, we can know that the decomposition rate of fungus is sensitive to environmental changes, so the **adaptability and viability** of fungi are considered prior to the expansion rate of fungi. Moreover, when different fungi are combined, the temperature and moisture niche width that the whole system have should be maximized.
- When the above two conditions are satisfied as much as possible, we should choose the combination of fungi that expand as fast as possible, because they show great advantages when we do not consider the environmental impact in our initial model.

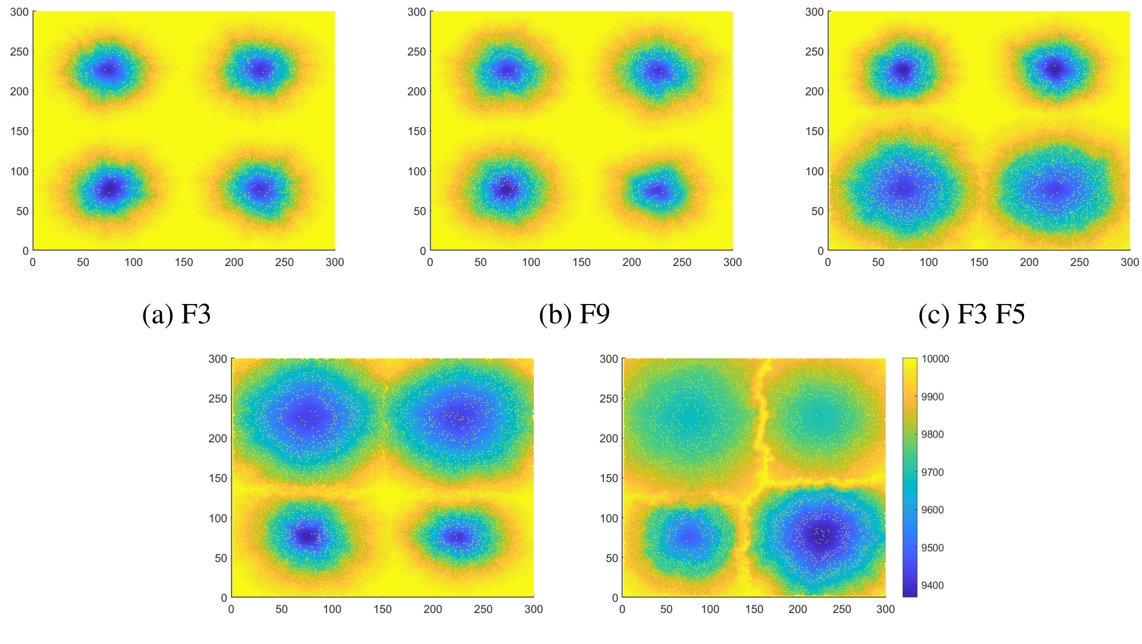
According to the previous rules, we can set 5 groups with the same initial numbers of fungi and the same initial positions.

Table 2: Groups Setting

	Group 1	Group 2	Group 3	Group4	Group5
Fungi choose	F3 × 4	F9 × 4	F3 × 2 & F5 × 2	F11 × 2 & F12 × 2	F7, F8, F11, F12
Moisture width	1.32	1.57	1.35	5.17	5.17
Temperature width	15.8	18.6	25.0	28.5	29.1

6.2 Results

In the simulation of this section, we fixed the trend of temperature and moisture to be similar to that of semi-arid area and use cellular automata model to run for 1000 days. The following Fig.(37) shows the remaining wood thickness for the five different groups of fungi.



(a) F3 (b) F9 (c) F3 F5

(d) F11 F12 (e) F7 F8 F11 F12

Figure 37: Remaining wood thickness.

In order to analyze the process better, we draw the change relationship of the remaining proportion of trees during the process. We set the overall thickness of the wood to be very large in order to maintain the stability of the system.

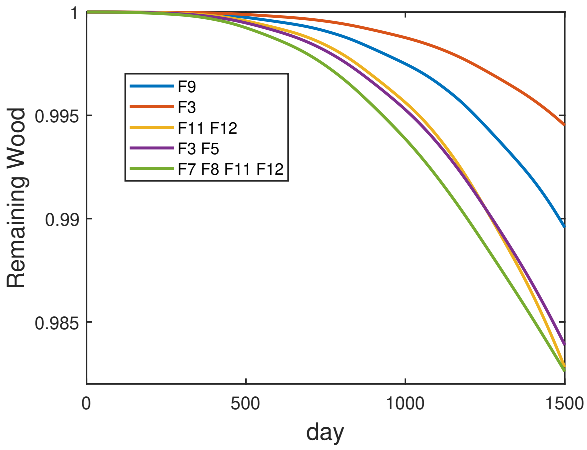


Figure 38: Changes in mass of wood.

From Fig.(38), we can conclude that when environmental factors are taken into account, biodiversity affects the decomposition rate of fungi. When the total number of fungi and the changing trend of the environment remained unchanged, the decomposition efficiency of the system with four different kind of fungi can reach **twice** as high as that of a single kind and **1.25 times** as high as that of two kinds.

However, there are preconditions for the conclusion in the previous paragraph, which are **stability of biodiversity** and **adaptability and viability** of fungi. Only when these conditions are fully met can we say that the system has **real biodiversity**.

7 Conclusion

The topic of the whole project comes from the importance of the role fungi play in carbon cycle: decomposing wood material and litters. Factors include environmental fluctuation, competition between species, overall climate condition as well as the diversity of species are considered to explore their effect on fungi's growth and wood decomposition.

First, we use mathematic modeling to simulate the whole decomposition process. The decomposition rate is calculated accurately considering only two main factors: extension rate and moisture tolerance. The compete rankings are set using Elo system. And finally CA modeling is used to show the process of competition and dynamic growth of the fungi. To make the result more vivid, we add visualization such as mapping, line charts and surface plot.

Then we add the environmental fluctuation and variation of weather patterns into our model to further modify the extension and decomposition rate of each fungus, considering their best growing temperature and moisture range. We categorized 2v2 competition into different endings. By comparing the competition result and the curves they present before and after adding external environment change, we conclude that environmental change not only affect their normal growth, making their curve less smooth, but also increase the time stronger fungus needs to win with the possibility of even reversing the win-lose situation.

After that, we increase the competition into 12 species and five different climates: tropical, arid, semi-arid, temperate and arboreal. For each climate, we categorized all 12 fungi into different advantages and disadvantages regarding the annual weather change. Also, we predict the possible combination of fungi species based on a large amount of testing using the established model.

Finally, we considered the influence diversity has on the decomposition of wood materials. By comparing the number of species and their consumption of the wood under same external conditions, we conclude that a rich biodiversity has an obvious positive effect on the efficiency of consuming materials, thus pushing the whole carbon cycling system.

8 Sensitivity Analysis

In section 5.4, we have proved that our model is **sensitive to the rapid and drastic changes of temperature and moisture**. This is because different fungi have different optimal temperature and moisture. In our model, although the behavior pattern of each cell is complex, the overall behavior pattern of fungi is predictable according to some existing rules and our simulation results is exactly consistent with these rules.

Initial location is also an important factor affecting the final results. So in the process of solving all the previous models, the initial position of fungi is fixed. Here we tested whether the initial position of fungi will have a great impact on the final area occupied by it when there are multiple fungi exists.

The following Fig.(39) shows the results of the sensitivity analysis of the initial position. We fix the temperature and moisture and choose three different fungi (F5/F9/F12) for testing. Before each run of the cellular automata, we randomly generate initial positions for the three fungi and repeate the simulation for 50 times. Finally, we fit three curves for them using Matlab and because the slope of the three curves is close to 0, we can conclude that our model is **insensitive to the initial position of the fungus when the number of tests is large enough**.

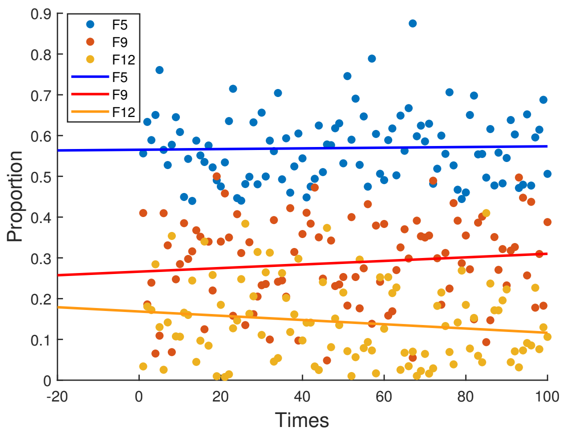


Figure 39: Algorithm schematic

9 Strength and Weakness

9.1 Strength

- A scientific and accurate simulation model is established by using **cellular automata** in MATLAB. **Excellent visualization** of fungal growth process makes the output of the model more intuitive, and also adds a lot of fun when solving the model.
- **Continuous problem discretization**: It is easy to update the model and consider more influence factors. It also enhances the robustness of the model and makes the model more stable.
- We simulate the influence of temperature and moisture in a very **large range**, including long-term and short-term simulation under eight different conditions (Boston/completely random fluctuation/fixed value/five climates). Lots of testing is performed to find persisting combinations.

9.2 Possible Improvements

- In our model, we only consider the competition relationship between fungi, but there are **other relationships** between them, such as cooperation.

- As the model becomes larger and larger, the **time** required to run a simulation code will become correspondingly longer for 12 species on a 300×300 map. So when all the factors were taken into account, there maybe ways to simplify the process, thus saving time.

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A Fungus species data

Table 3: Fungi data

	Name	E_0	T_{min}	T_{max}	m_{min}	m_{max}	R
F1	Armillaria_gallica_FP102531_C6D	0.25	6.4	31.1	0.45	3.46	0.232
F2	Armillaria_gallica_HHB12551_C6C	0.49	15	31.2	0.19	4.34	0.000
F3	Armillaria_tabescens_TJV93_261_A1E	1.07	16.3	32.1	0.11	1.43	0.000
F4	Fomes_fomentarius_TJV93_7_A3E	4.71	20.8	30.1	0.1	1.29	0.285
F5	Hyphodontia_crustosa_HHB13392_B7B	1.96	7.1	30.3	0.09	1.28	0.569
F6	Lentinus_crinitus_PR2058_C1B	6.38	22.4	40.2	0.13	1.68	0.569
F7	Merulius_tremullosus_FP102301_C3E	10.62	16.6	34.2	0.12	1.31	0.788
F8	Phlebiopsis_flavidoalba_FP150451_A8G	10.8	15.7	32.7	0.27	2.81	0.986
F9	Phellinus_hartigii_DMR94_44_A10E	1.54	9.6	28.2	0.42	1.99	0.493
F10	Phlebia_acerina_MR4280_B9G	8.75	13.6	31.3	0.1	1.29	1.000
F11	Tyromyces_chioneus_HHB11933_B10F	3.88	19	33.6	0.08	1.27	0.805
F12	Xylobolus_subpileatus_FP102567_A11A	0.77	5.1	33.6	0.29	5.25	0.493

8.1 The Roles of Fungi in Ecosystems

Figure 1: Aspergillus Flavus, a species of fungus.

Fungi are saprophytic organisms that decompose organics for a living. Moldy food, moldy closes, poisonous mushrooms… Although fungi bring a lot of troubles to people's daily life, they are actually making very important contributions to the world we live in. Recent scientific research has revealed the significant roles that fungi play in ecosystems, which we are going to learn in this chapter.

8.1.1 Carbon Cycle and Wood Decomposition Process

Fungi are one of the primary decomposers of ground litters and woody fibers. Without the decomposers, the *organic carbon* in dead plants can not be turned into *inorganic carbon* and get recycled in the carbon cycle of ecosystems. Therefore, the existence of fungi influences the stability of ecosystems directly.

A recent study by scientist shows that, different species of fungi have great diversity in their traits, such as *hyphal extension rate* and moisture tolerance. Generally, the fungi with high extension rate and competitiveness tend to be less adaptable to different environmental conditions, and those with wider *moisture/ temperature niche widths* usually grow slower. In the wild, there are usually multiple fungi species taking part in a wood decomposition process. Fig. 2 is the simulation of the decomposition process of a wood plate. Each circular dot on the pictures refers to a point of wood being decomposed. From the simulation, we can clearly see that different species of fungus extend and decompose the wood at different speeds. What's more, the boundaries of two adjacent dots are not as smooth as an arc, which indicates that there are some interactions between different types of fungi as they meet each other.

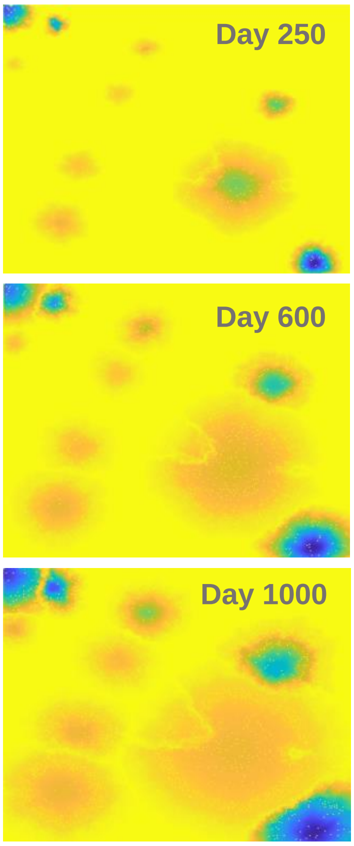

Figure 2: Simulation of the decomposition process of a woody plate by fungi (chromatic diagram). Deeper color means deeper degree of decomposition.

8.1.2 Interactions between Fungal Species and Adaptation to Different Environmental Conditions

The interaction patterns of fungi are related to many aspects, including hyphal extension rates, competitiveness, tolerance to environmental factors (humidity, temperature…), as well as the changes of environmental conditions. According to the results of computer simulations, there are four main types of interactions among fungi. Below are the types of interactions and corresponding features:

- *Overwhelming winning-losing*: One type of fungi grows overwhelmingly better than the other one. The weaker type of fungi will be driven out nearly at once. Usually only happens in experimental conditions with constant temperature and humidity.
- *Quickly determined winning-losing*: Similar to the overwhelming winning-losing type. The difference is, the weaker fungus can stay existing for a short time and occupy a small area of wood.
- *Deuce at first*: There is no obvious trend of winning-losing at first. However, one species will be gradually driven out after some time.
- *Long-run competition*: There is obvious deadlock (even seesaw

battle) between two species. Usually the two species can live with each other for years.

The interaction patterns between fungi are not fixed, but varies under different environmental conditions. And the variability of environments assures that, those fungi being driven out of in some conditions many grow well in some other conditions.

Since some fungi can adapt to a broad range of temperature/ humidity while others can grow very fast in suitable environments, some combinations of several types of fungi are more stable, with higher growth rates in certain environments. For example, the pair *f.fom.n*[1] and *m.trem.n*[2] can live persistently in arid areas, and the pair *h.crust.n*[3] *and p.har.n*[4] tend to live in tropical rain forests stably.

8.1.3 Diversity of Fungal Communities and Biodiversity

As mentioned above, there is great diversity in fungal communities. Why should there be so many species of fungi? Is there any benefit for the community or the ecosystem? Lets see the result of am experiment by computer simulation:

In the experiment, there are five groups of fungi. Each group has the same number of initial colonies and is place on a wood plate. The only difference between the groups is the number of species in each group. The result is: the decomposition efficiency (described as the amount of wood decomposed in a certain period of time) of the group with four different species reaches twice of the efficiency of the group with a single species, and 1.25 times of the group with two species.

The above result indicates that: the higher the diversity is in the fungal community, the higher efficiency of ground litter decomposition is. The high diversity of fungi communities also maintains the stability of the community. Because when there are some fluctuations or changes happening in the environment, higher diversity of species assures higher probability for fungi to adapt to the new conditions, thus more opportunity for the carbon cycle of the ecosystem to stay steady. What's more, higher diversity of fungi means that more different types of dead plants can be decomposed. This indicates that the number of plant species able to exist in the ecosystem will be larger. As a result, the number of animal species will also be larger, and the total *biodiversity* will also be higher.

In conclusion, the main contributions of fungi to ecosystems are:

- Decomposing the ground litter
- Assuring the regular operation of carbon circle.
- Improving the biodiversity in ecosystems.

1 *f.fom.n*: short name of *Fomes_fomentarius_TJV93_7_A3E*, a species of fungi.
2 *m.rem.n*: short name of *Merulius_tremullosus_FP102301_C3E*, a species of fungi.
3 *h.crust.n*: short name of *Hyphodontia_crustosa_HHB13392_B7B*, a species of fungi.
4 *p.har.n*: short name of *Phellinus_hartigii_DMR94_44_A10E*, a species of fungi.

Glossary

organic carbon:

A form of carbon which is existing in organic substances, such as glucose.

inorganic carbon:

A form of carbon existing in inorganic substances, such as carbon dioxide.

hyphal extension rate:

The extension rate of fungal hyphae, which describes the growth rate of fungi. Usually with the unit of mm/day.

moisture/ temperature niche widths:

The difference between the maximum and minimum moisture/ temperature levels in which half of a fungal community can maintain its highest growth rate.

biodiversity:

The variety of life in the world or in a particular ecosystem.

Reflection Questions

Q1: If fungus A grows faster than fungus B and it is more competitive, which species tends to tolerate a wider range of moisture? Please give your explanations.

Q2: Describe the four typical categories of interactions between different species of fungi.

Q3: List at least three benefits that a fungal community with multiple species brings to the local ecosystem.