Problem Chosen	2021 MCM/ICM Summary Sheet	Team Control Number
A		2112048

Simulated Fungi Decomposition System

Summary

Fungus plays an important role in decomposing the organisms and promoting the carbon cycle. Different fungus may have different decomposition ability and adaptability to the changing environment. Therefore, it is of great significance to study how to improve the decomposition efficiency through biodiversity simulation.

In order to incorporate the fluctuations of the environment into our model, we design the **Environment-Fungi Coefficient Abstraction(EFCA)** to quantify the impact of **PH, temperature, moisture and light intensity** to the fungus communities. We set up the environment index E to precisely determine the growth rate, death rate and decomposition rate of the specific fungus community. Based on biological knowledge and mathematical principles, we justify the functions we choose for the three rates are suitable through data fitting and error testing using Matlab tool packages.

We then set up the **Fungi Life Cycle Model**for single fungus community. The simulation of the decomposition process is carried out through **Cellular Automata** to visualize the decomposition process. We design the transition rules based on biology properties of fungi. Based on the model with only one fungus group, we extended the model to **Dynamic Fungi Life Cycle Model** for systems with more than one fungus communities. In the model, we design the transition rules based on the competitive ranking of different fungus groups to describe **the interaction between different fungus groups**. The algorithm we used for our model follows the biology principles to evaluate each cell in the Cellular Automata, guaranteeing the accuracy of the model. It turns out in the short term, the fungus community with a higher competitive ranking would survive the one with a higher tolerance. But in the long term, the result is just the opposite, which corresponds to the research result that there is a **trade off between tolerance and dominance**.

One of the highlights of our simulation is the sensitivity analysis we conduct to show the significance of **biodiversity**. We choose two fungus communities of different biology properties. Under periodic variation of moisture, fungi with higher competitive ranking but lower moisture tolerance may survive the fluctuations within smaller range, but fail to survive the rapid environmental changes. The biology property of trading off between dominance and tolerance highly requires biodiversity of fungus community to improve the efficiency of decomposition. In addition, we simulate the system in different environments such as **arid, semi-arid, temperate and tropical forests** to test the stability of the system. **Seasonal changes of temperature and moisture** are also included. Taking gravity into consideration, we innovate the model for arboreal fungi to investigate different fungus species.

Through our dynamic model and sensitivity analysis, we demonstrate the significance of biodiversity not only in improving the efficiency of decomposition and carbon cycle but also in surviving the fluctuating environment. Our model features convenient implementation and accurate record of the decomposition process. Different environment settings can be achieved through easy changes of coefficients.

Keywords: Cellular Automata, Dynamic Life Cycle Model, Sensitivity Test, Environment-Fungi Coefficient Abstraction, Period Change and Environmental fluctuations

Contents

1 Introduction

1.1 Problem Background

In the geochemical cycle on the Earth, fungus plays the important role of "decomposers" by breaking down organic materials into small molecule carbon compounds to be renewed in the next rounds of carbon cycles. Real ecosystems feature the biodiversity of all species to achieve balance and sustainability. The decomposition rate of fungus when decomposing ground litter and woody fibers is not only relevant to individual fungal activity but also influenced by dynamic interactions between different species of fungi. To achieve accurate simulation of the real environment, environmental indexes would be incorporated to testify the sensitivity of the system.
In this paper, we attempt to explore a system of various fungus communities decomposing ground litter and woody fibers in different local environments to see how biodiversity matters in variation of environments. First of all, we would use Environment-Fungi Coefficient Abstraction to quantify how different environment indexes would influence the fungus(i.e., the growth rate G, the death rate D, the decomposition rate F). Secondly, we would build the Fungi Lifestyle Model(FLM) to simulate how one single fungus community would decompose the woody fibers under specific environmental conditions and derive the decomposition rate. Thirdly, we plan to involve biodiversity by combining FLM for different fungal species together, which are weighted by competitive ranking of different species. Furthermore, we would test the sensitivity of the multi-fungal performance model to the changing environments through studying the fluctuations of different environmental indexes.

1.2 Literature Review

pH and temperature sub-factor model: Work done by Alaa Mohsin Al-araji et al[1] reveals that fungus growth is highly relevant to temperature and pH value. In their work, they studied the growth of various types of fungi from pH 3 to 11, as well as temperature from 20 to 40 degrees. They collected the growth data and provided graphical results on the distribution of different fungus' growth over different pH and temperatures.

Moisture sub-factor model: In the work done by G.Ayerst et al[2], various fungi were measured throughout the ranges of moisture and temperature which permitted growth. The result shows that there were significant differences between species in their temperature and water activity optima and limits, the relevance among those factors was also illustrated in the article

Light sub-factor model: Paulami Koley et al[3] shows that Light intensity plays a crucial role in conferring variation of hyphal growth and branching. They evaluated the hyphal behavior in terms of its growth and branching patterns. With a deep observation on the effect of light on fungi growth and branch, the author discovered that the culturing of the fungus in different light intensities of 120, 20, 5 lux and darkness show that a low light intensity is best for its growth. In their work, photographic records of the experiment result are provided for further use.

2 Model Overview and Notation

2.1 Two fungi used in our model

The two fungi we use in our model are shown in Figure 1[1]. The left one is Armillaria gallica(denoted but green color) which has a slow-growth rate but has a good moisture tolerance while hlebiopsis flavidoalba(denoted by blue color) has the opposite properties.

Figure 1: Armillaria gallica and Phlebiopsis flavidoalba

2.2 Model Overview

Task 1 We conduct Environment-Fungi Coefficient Abstraction (EFCA) to quantify growth rate G, death rate D and decomposition rate F with respect to environment factors.

Task 2 Based on G, D and F, build Fungi Life Cycle Model for one fungus community.

Task 3 Taking biodiversity into consideration, update G, D and F into dynamic G, D and F and simulate the decomposition with two different fungus communities.

[1]Copyright Dan Molter(left), Jerzy Opioła(right), reproduced under CC BY-SA 3.0 license

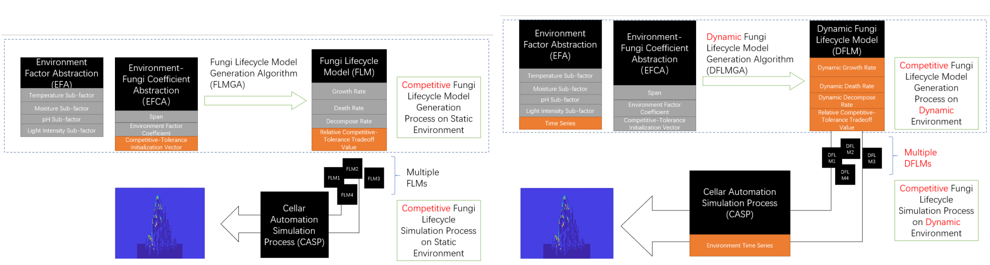


Figure 2: Explanation on Task 2(left) and Task3(right)

Variable Name	Description
E	Environmental factor defined in Equation 1
D	Death rate (The proportion of dead cell in one period)
F	Decomposition rate (The proportion of wood become air)
G	Growth rate (The proportion of cells grows out new cell)
$SPAN$	The maximum live period for the fungus
t	The global period for all cells
t_0	The period for each fungus cell to live
LT	light intensity
T	Temperature in Celsius
M	Moisture sub-factor
P	PH value
Fl	Fluctuation factor

Table 1: Notion list

Task 4 Change the environment indexes to test the sensitivity of the multi-fungi system in different weather patterns.

2.3 Notations

The notations used in the paper is listed in Table 1.

3 Fungi Life Cycle Model

In this session, we will use PH of the surrounding environment, temperature, moisture and light intensity to simulate the environment that the fungus communities are living in. We study several papers to determine the quantitative relationship between the environmental conditions and the growth rate, death rate and the decomposition rate.

3.1 Model Principle

The environment factor E would be the independent variable determining the growth rate of the fungus community-$G(t)$, the death rate of the fungus community-$D(t)$ and the performance of decomposition(i.e. the decomposition rate)-$F(t)$. We require $G(t)$, $D(t)$ and $F(t)$ to be numbers between $(0, 1)$, following the scale of E. Then G, D and F would be used in further models to simulate the decomposition performance of the fungus community.

3.2 Model Assumptions

- The graph with **PH** on X-axis and **PH sub-factor** P on Y-axis follows the graph of the normal distribution.
  Justification: According to the journal European Academic Research, PH of the environment exerts

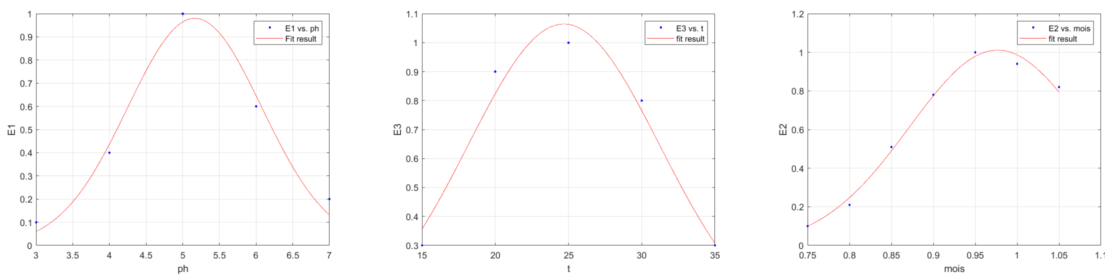


Figure 3: The graph for P, T and M

important impacts on the growth of the fungi. Fungi generally grow well in acidic conditions, but some species favor neutral to slightly alkaline conditions.
Then we apply the Curve Fitting Tool Box package in Matlab to find out the best fitting function of the data. It turns out that the graph of normal distribution fits the data best(see the left-most figure in Figure 3).

- The graph with **temperature** on X-axis and **temperature sub-factor** T on Y-axis.
  Justification: The journal European Academic Research also demonstrates that there is a significant difference between fungal growth curve under different temperatures. The best studies temperatures are 30°C, 25°C, 20°C, 35°C then 40°C respectively.
  Then we apply the Curve Fitting Tool Box package in Matlab to find out the best fitting function of the data. It turns out that the graph of normal distribution fits the data best(see the middle figure in Figure 3).

- The graph with **moisture** on the X-axis and **moisture sub-factor M** on the Y-axis follow the graph of the normal distribution.
  Justification: The paper from Woverhamp College of Technology observed over 100 individual growth rate tubes to plot the graph of moisture and the average growth rate of the fungi communities.
  Then we apply the Curve Fitting Tool Box package in Matlab to find out the best fitting function of the data. It turns out that the graph of normal distribution fits the data best(see the right-most figure in Figure 3).

- The graph with **light intensity** on the X-axis and **light intensity sub-factor LT** on the Y-axis follows the following relationship:

$$LT = \begin{cases} 0 & \text{if environment is dark} \\ 0.5 & \text{for most general cases} \\ 1 & \text{if the light is set at the most suitable intensity} \end{cases}$$

  Justification: The paper from Research Journal of Life Sciences, Bioinformatics, Pharmaceutical and Chemical Sciences conducted several experiments to investigate the impact of light intensity on the growth of the fungus community.
  They found out that for all the conditions except the dark condition, the fungus community would grow better as the light intensity grows. To simplify the model, we would abstract this positive correlation into three indexes between $(0, 1)$, which would be added into the model later.

Following the biology fact that fungi can only survive the environment where all the conditions are suitable, E should be a factor sensible to even very tiny change in its sub-factors. To maintain this property, we

choose the geometric meaning instead of other sample statistics.
E is defined as the geometric mean of PH sub-factor P, temperature sub-factor T, moisture sub-factor M and light intensity factor LT.

$$E = \sqrt[4]{P \cdot T \cdot M \cdot LT} \tag{1}$$

3.3 Construction of G, D and F with regard to E and t

We define G,D and F to be the rate result in $(0, 1)$. And for every fungi species, the life span of the fungi are represented as SPAN. To simulate the performance of one specific fungi species under a certain environment, we first define G, D and F as functions about E, not considering the time t. Then we would involve t in the model to see the change throughout the whole process:

3.3.1 Growth Rate G with respect to E, t:

The function of G with regard to E should follow the following principle:

- G increases as E increases.
- Since fungi can only survive the environment where all the conditions are suitable, we predict that G would be pretty small when E is low. But G would grow fast once E achieves some point which is the lower boundary of the interval of E that is suitable for the fungus community to survive. So we choose an exponential to describe G's change as E varies.

Concluded from the discussion above G with regard to E is:

$$G(E) = e^{E-1} \tag{2}$$

Take t into consideration:

- $t \in (0, SPAN)$
- When t is close to $\frac{SPAN}{2}$, which means the fungi are at its young and middle age, G should be relatively high, close to 1.
- When t is close 0 or SPAN, which means the fungi are almost newly born or on the verge of death, G should be relatively low, close to 0.

So G with regard to E and t is:

$$G(E, t) = \frac{-4e^{E-1}t(t - SPAN)}{SPAN^2} \tag{3}$$

3.3.2 Death Rate D with respect to E, t

The function of D with regard to E follows that D decreases as E increases, so we expect D to be in negative correlation with E. Taking t in to consideration:

- $t \in (0, SPAN)$
- D increases as E decreases.

- When t is close to SPAN, which means the fungi are almost on the verge of death, G should be relatively high, close to 1.

So D with regard to E and t is:

$$D(E,t) = (\frac{t}{SPAN})^E \tag{4}$$

3.3.3 Decomposition Rate F with respect to E, t

The performance of F with respect to E is always a positive correlation. For every fungus community, we quantify their decomposition rate(the efficiency of decomposing the woody fibers) to be equal to the value of E since E for different fungus communities integrates their own biology features into the corresponding environment.
To conclude,

$$G(E,t) = \frac{-4(e^{E-1}t - SPAN)(e^{E-1}t)}{SPAN^2} D(E,t) = (\frac{t}{SPAN})^E F = |E| \tag{5}$$

4 Fungi Life Cycle Model

Based on the Environment Fungi Coefficient Abstraction we completed in the last section, we would use Cellular Automata to simulate the decomposition process of the one kind of fungus on woody fibers.

4.1 The use of Cellular Automata

Cellular Automata enables us to initialize the transition rules and possible states of cells of interests based on our needs. Then we can repetitively apply the transition rules to cells and update their states. Keeping record of the chronological change of the Cellular Automata contributed to the analysis of the dynamic development.

4.2 Restatement of the Problem

The problem can be simplified as how fungi, wood and air would interact with each other under different conditions. We will initialize the model by setting three basic elements: fungi, wood and air. By setting up a 3-face Cellular Automata model, we will simulate the process that the fungi decompose the wood into air and how fungi grow, move and die. Therefore, in our model: every cell has three possible initial phases: wood, fungi and air as shown in left side of Figure 4.

4.3 Model Rules

During the decomposition process, the fungus only has 4 possible activities:

1. Grow: A new fungus can grow in non-wood cells whose nearby cells must have at least one wood cell. The possibility of growth has been calculated in the last session, i.e. the growth rate, G.
2. Die: A fungus has the possibility to die at a specific time during its life based on the environment. The possibility of death has been calculated in last session, i.e. the death rate, D.

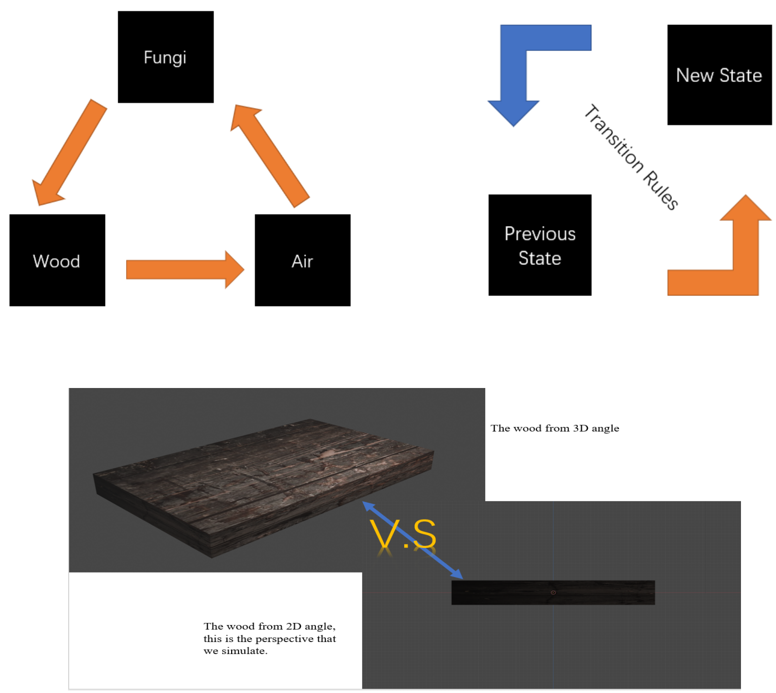


Figure 4: Schematic diagrams showing the state transition in Cellular Automata

3. Decompose: A fungus would decompose the wood in its nearby cells. The decompose rate is defined as the possibility that a cell nearby a fungi will be reached to be decomposed.
4. Move: For fungus whose nearby cells are air, its movement, if possible, is only relevant to the impact of gravity. We would construct two different scenarios: one taking gravity into consideration, the other one not and the result is shown in Figure 7.

- Death Rule:
  Here are the 3 situations in which the fungus will die:
  1. Among the 8 nearby cells, there is no wood cell.
  2. When time t is larger than the span of the fungus, the fungus will die.
  3. When the fungus has at least one wood cell around it, and t is still in the span, we would randomly pick a number x in (0,1).

     If $x \leq D$, the fungus will die.
     If $x > D$, the fungus will stay alive.

  For conditions other than the above three conditions, the fungus will stay alive.

- Growth Rule: For a fungus to go through the mitosis stage and double itself, the fungus cell should satisfy all of the following conditions simultaneously:
  1. Among the 8 nearby cells, there is at least one wood cell to provide necessary nutrition for the fungus to have mitosis.

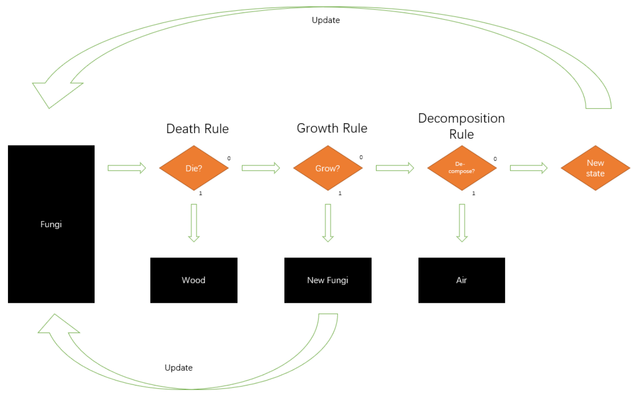


Figure 5: Flow chart for the algorithm for single species

2. There is at least one air cell within the fungus's reach to place the new fungus born during the mitosis.
3. We randomly pick a number x in (0,1).

$$\text{If } x \leq G, \text{the fungus will go through the mitosis and double itself.}$$
$$\text{If } x > G, \text{the fungus will not go through the mitosis.}$$

In case one of the above situations is not satisfied, the fungus can not go through the mitosis stage and double itself.

- Decomposition Rule:
  For a fungus to decompose the adjacent wood into air, we would use the decompose rate we get in the previous session to conduct the process:

  1. Compute the result of 8 times decomposition rate and round it off to the nearest integer to see how many wood cells may be decomposed in the nearby 8 cells, denote the number as 8.
  2. Pick 8 cells randomly from the nearby 8 cells of the fungus cell. If the cell is wood cell, then it will be decomposed to air. If not, the corresponding cell will stay the same.

4.4 Steps of Algorithms

Step 1 Evaluate whether the fungus is dead or not using the "Death Rule".
If dead, update the corresponding cell to be wood. If not, move on.

Step 2 Evaluate whether the fungus will grow, i.e. doubling itself into two fungi using the "Growth Rule".
If so, update the state of the corresponding cell to be fungus and apply the algorithm from the start again. If not, move on.

Step 3 Study all fungus cells one by one to get the new state of all wood cells using the "Decomposition Rule".
If the wood cell is decomposed, update its state to be air. If not, keep its original state.

Step 4 Update all the changes in the information matrix.

Step 5 Start over again with the updated information matrix.

4.5 Results and Analysis

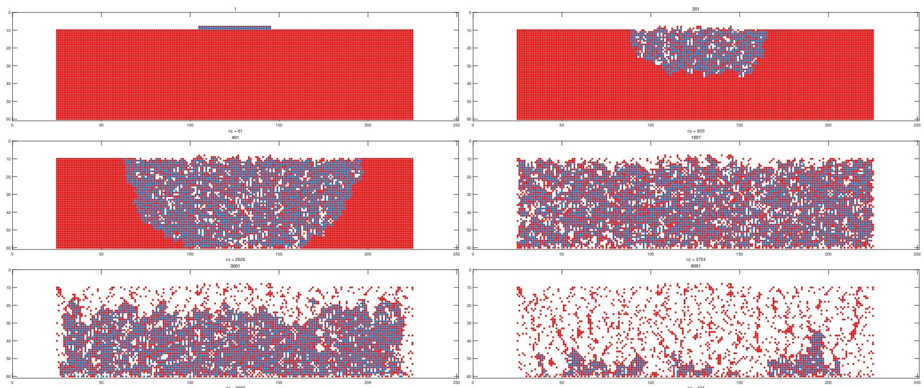


Figure 6: The above pictures are the process that the blue fungi decompose the red wood. Taking gravity into account, the fungi will start from the top of the wood and go down till the bottom.

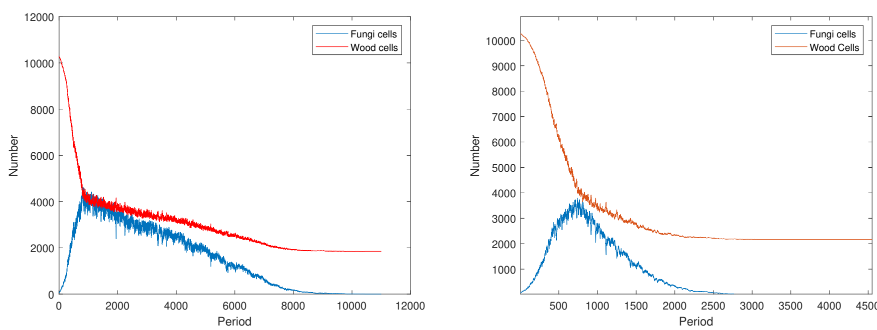


Figure 7: The above pictures depict how the numbers of fungi cell and wood cells change with regard to the number of mitotic cycles. The left one takes gravity into the consideration while the left one not.

We can see from the results that no matter whether we take gravity into consideration or not, wood will not be totally decomposed by the fungi. And the system will end up in a balanced state as the number of fungus cells and wood cells will stay at constant levels.

5 Dynamic Fungi Life Cycle Model

Based on the Fungi Life Cycle Model that we constructed for each different kind of fungus, we now combine life cycle models for different fungus together to simulate the biodiversity in the real environment. The interaction between different fungus communities is combined based on the their competitive rankings.

5.1 Restatement of the Problem

Starting from the Fungi Life Cycle Model only for one species, we first run the model for every species that we plan to put in the dynamic model. We then store the information matrix for each species in separate sheets. Suppose we have n different fungus in the system, then we would get n different sheets with information matrix. Then we put all the sheets together, use the "Battle and Survive Rule" to determine the state of each cell. The information matrix we get after combination will be the result for the system of different fungi.

5.2 Construction of dynamic environment index E, growth rate G, death rate D, decomposition rate F.

To measure the growth rate, death rate and decomposition rate for different fungi under the same environment, we update our Environment Factor Model of Fungi Life Cycle in the following way:

1. Denote t0 the global time: the evolution time of the whole system, measured by the number of mitotic cycle that the system has existed.
2. Denote P_{t_0}, T_{t_0}, M_{t_0}, LT_{t_0} as the value of the four sub-factor for the four environment indexes PH, temperature, moisture and light intensity.
3. Denote r as the competitive ranking factor the fungus among all the fungi in this system, SPAN as the span of the fungus.
   Then for every fungus group in the system, following the geometric mean we take in the previous section:
$$E_{t_0} = \sqrt[4]{P_{t_0} \cdot T_{t_0} \cdot M_{t_0} \cdot LT_{t_0}} \tag{6}$$

Now we update G, D, F with new environment index E_{t_0}:

5.2.1 Dynamic Growth Rate $G(E_{t_0}, t)$

The principle that growth rate G follows is the same as that in Section 3.3.1, as the interaction between different fungus group will not influence the growth of a single fungus community.

$$G(E_{t_0}, t) = \frac{-4t(t - SPAN)e^{E_{t_0}-1}}{SPAN^2} \quad t \in (0, SPAN) \tag{7}$$

5.2.2 Dynamic Death Rate $D(E_{t_0}, t)$

In addition to the principles mentioned in Section 3.3.2 that the death rate D should follow, with regard to the system with different fungi, new added principles are as following:
It is clearly stated in the question that: "The slow growing strains of fungi tend to be better able to survive and grow in the presence of environmental changes with respect to moisture and temperature, while the faster growing strains tend to be less robust to the same changes". Therefore, the dynamic death rate should satisfy:

1. As G decreases, D decreases.
2. As the fluctuation of E(i.e.the moisture and temperature) grows, D increases. We would use $\frac{\partial E}{\partial t}$ to describe the fluctuation of the environment as time flows.

3. Following the definition of moisture tolerance stated in Figure 2 in the original problem prompt, we can see there is a trade off between moisture tolerance and competitive ranking.
   So we define a trade function f:

$$f(r) = -\frac{1}{2}r + \frac{1}{2} \quad r \in (-1, 1), f(r) \in (0, 1) \tag{8}$$

   As $f(r)$ grows, the moisture tolerance of the fungus decreases, D increases.

So:

$$D(E_{t_0}, t) = (\frac{t^2}{SPAN^2})^{\frac{E_{t_0}}{f(r \cdot G(E_{t_0}, t) \cdot \left| \frac{\partial E}{\partial t} \right| + 1}} \quad t \in (0, SPAN) \tag{9}$$

5.2.3 Dynamic Decomposition Rate

Since the interaction between different fungus groups will not influence the growth of a single fungus group, the principles for the decomposition rate of the fungus in a multi-fungi system will stay the same.
So:

$$F(E_{t_0}, t) = E_{t_0} \tag{10}$$

5.3 Model Rules

We will still apply all the rules mentioned in Section 4.2 to the new dynamic fungi life cycle model. To regulate the evaluation of interaction among different fungi groups, we now add in a new "Battle and Survive Rule":
Suppose there are in total n different fungi in the system. For the cell whose corresponding position in the information matrix is (x,y), then (x,y) of the information matrix for the dynamic fungi life cycle model would be:

1. For all n information matrices of single fungus, if the (x,y) cells are all fungi, then the (x,y) cell of the dynamic system would be the fungi with the highest competitive ranking.

2. For all n information matrices of single fungi species, if there is at least one (x,y) cell is wood, then the (x,y) cell of the dynamic system would be wood.

3. The rest of cells of the dynamic system would be air.

5.4 Steps of Algorithm

For each sheet(represented by `S(:,:,i)` in Matlab) of information matrix S, conduct the following steps for every different fungi:

Step 1 Evaluate whether the fungus is dead or not using the "Death Rule". If dead, update the corresponding cell to be wood. If not, continue.

Step 2 Evaluate whether the fungus will grow, i.e. doubling itself into two fungi using the "Growth Rule". If so, update the state of the corresponding cell to be fungus and apply the algorithm from the start again. If not, continue.

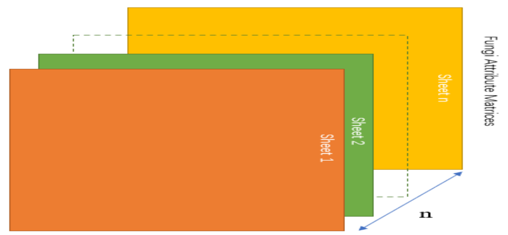


Figure 8: Schematic diagram on how we store data in Matlab for multiple fungi

Step 3 Study all fungi cells one by one to get the new state of all wood cells using the "Decomposition Rule". If the wood cell is decomposed, update its state to be air. If not, keep its original state. Combine all the results for different sheets.

Step 4 Use the "Battle and Survive Rule" to determine the state of each cell after combination.

Step 5 Update all the changes in the information matrix S after combination.

Step 6 Go back to Step one untill the maximum period.

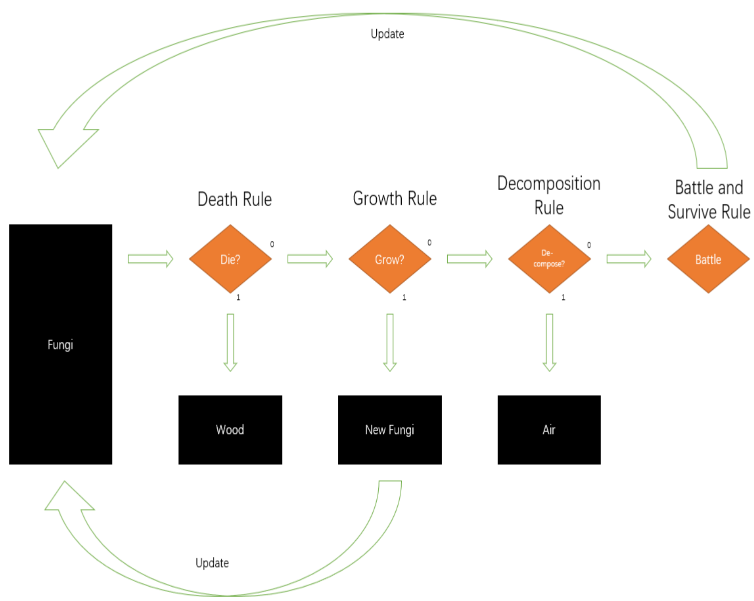


Figure 9: Flow chart for the algorithm of multiple species

5.5 Short-term and Long-term Results of the Dynamic Fungi Life Cycle Model

We control the difference between short-term cycle and long-term cycle through the number of the mitotic periods that the whole program will go through. Short-term results are the state of the system within 1000 mitotic periods. The long-term results are the state of the system evolving for more than 1000 mitotic periods.

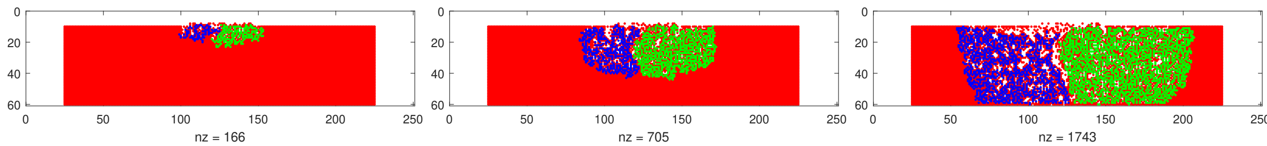


Figure 10: The Short-term results for the Dynamic Fungi Life Cycle Model with $t = 101, 301, 601$ representing the short term

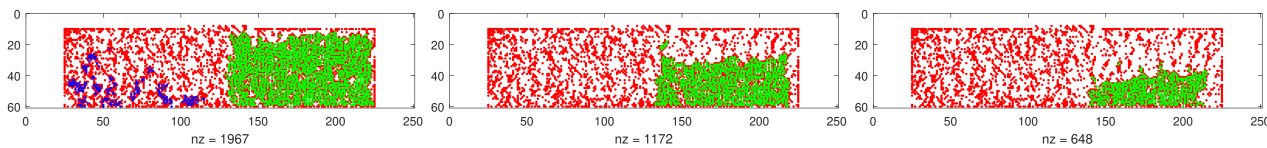


Figure 11: The Long-term results for the Dynamic Fungi Life Cycle Model with $t = 2001, 6001, 9001$ representing the long term.

Figure 10 and Figure 11 depict the situation that the blue fungus have a higher competitive ranking while the green fungi have better moisture tolerance. In the short term, the blue fungi outweigh the green one as blue fungi can replace the green fungi on the verge of the two different groups. While in the long term, the green fungi fits the environment better. So in the end, the number of the green fungi cells is larger than the blue fungi cells.
The comparison between the short-term and long-term result implies that in the competition of the real world, all the species follows the rule "Survival of the Fittest".

6 Sensitivity Analysis on Single Varying Environment Factor and Multiple Varying Environment Factors

6.1 Sensitivity Analysis for Fungi Life Cycle Model

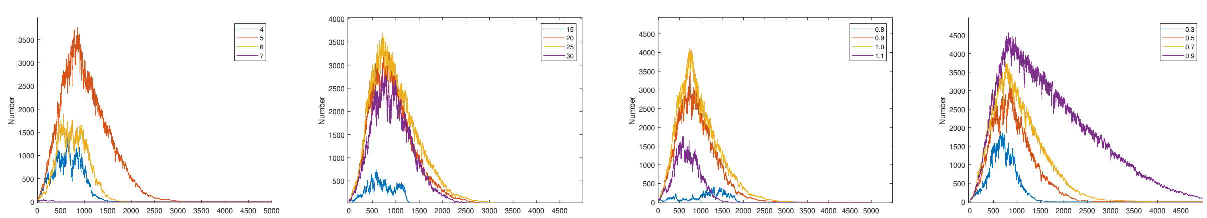


Figure 12: The number of fungi cells under different PH, temperature, moisture level and light intensity with respect to time.

Figure 12 illustrate that when only one environment factor changes, the peak value the number of the fungi cells can achieve and the time taken to reach the peak value would vary a lot. We may repeat the program many times to find out the best environment (i.e. the best PH, temperature, moisture level and light intensity) for every kind of fungus.

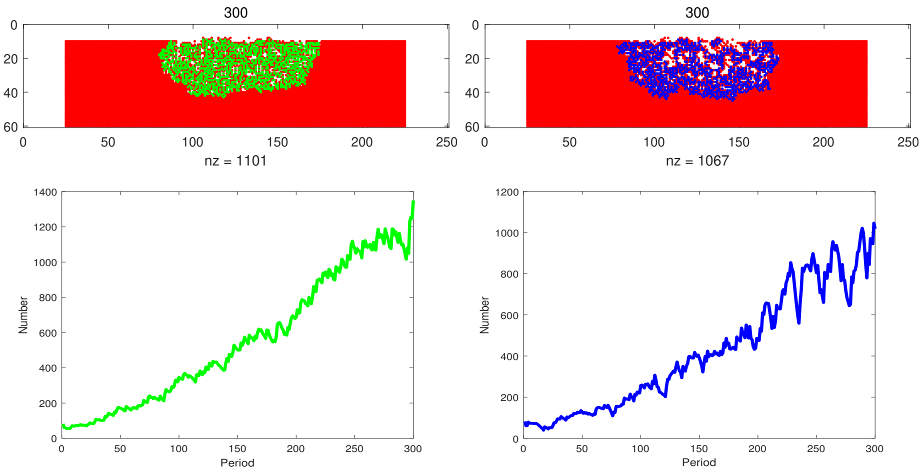


Figure 13: two single-fungi system under moisture fluctuations.

6.2 Sensitivity Analysis for Dynamic Fungi Life Cycle Model

In this section, we will simulate how the system with more than one fungi evolve in varying environment factors. We keep PH of the environment, temperature and light intensity constant and let moisture take a periodic variation. To see how fluctuation range impact the evolution of the system, we set three different fluctuation models of the Moisture Sub-factor M.

$$M = 0.9 + Fl \sin(\frac{1}{\pi}t) \tag{11}$$

with Fl representing the factor of the fluctuation. We look into two possible initial position of the two different fungi groups. The first one starts with two different fungi groups in a mixture arrangement. The second one starts with two different fungi groups gathering separately. All the figures show the state of the system when t is 300 mitotic periods. We give figures on the state of the system and the changing number of the two different fungi cells.

The blue fungi have a higher competitive ranking while the green fungi have better moisture tolerance. We first put the two different fungi in separate systems. It turns out that the number of the blue fungi follow the fluctuation of the moisture while the number of green fungi doesn't, indicating that the fungi with higher competitive ranking have lower moisture tolerance. This result is in accordance with the trade off between tolerance and moisture mentioned in the problem.

As we can see from the Figure 14 and Figure 15, the blue fungi have high competitive higher ranking but relatively lower moisture tolerance, so the blue fungi survive well in environment with small and medium moisture fluctuation, but fail to survive in the environment with large environment fluctuations. The change of the number of the blue fungi takes on a fluctuation pattern similar to that of the moisture, implying that the blue fungi are susceptible to the change of moisture.

On the other hand, the green fungi have relatively lower competitive ranking but better moisture tolerance, so it survives the rapid fluctuating environment better than the green fungi.

6.3 Dynamic Fungi Lifestyle Model under Different Environments

6.3.1 Arid and Semi-arid Environment

Arid and semi-arid environments both have relatively low moisture level, so the Moisture Sub-factor would be relatively low. We set the other environment factors at constant appropriate levels. It turns out that the

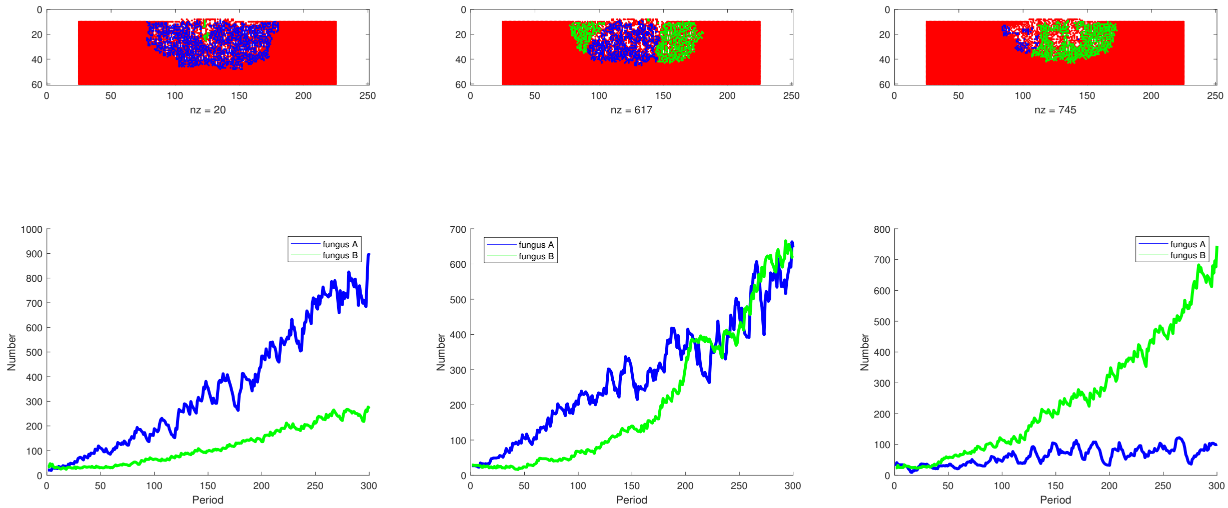


Figure 14: Two-fungi system under small, medium and large moisture fluctuation with mixture starting status.

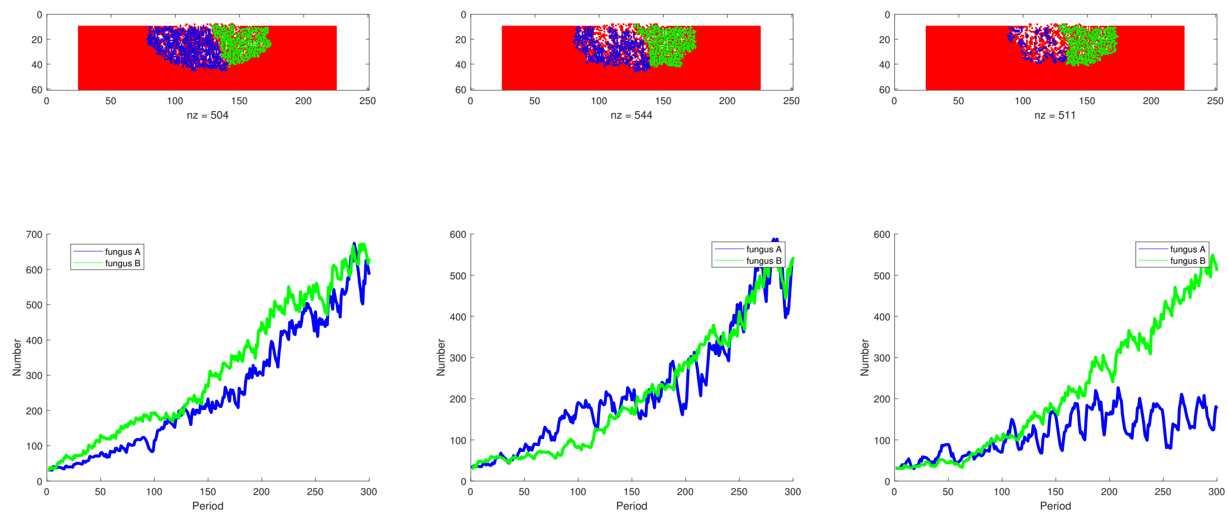


Figure 15: Two-fungi system under small, medium and large moisture fluctuation with separating starting status with $Fl = 0, 0.14, 0.2$

green fungi with relatively low competitive ranking but high moisture tolerance survive better blue fungi. This result indicates that fungi with better moisture tolerance can survive extreme environments better.

6.3.2 Arboreal Fungi

In regard to arboreal fungi, we need to reconstruct our model in the following ways:
Instead of placing the wood horizontally, we should visualize a wood in the vertical direction.

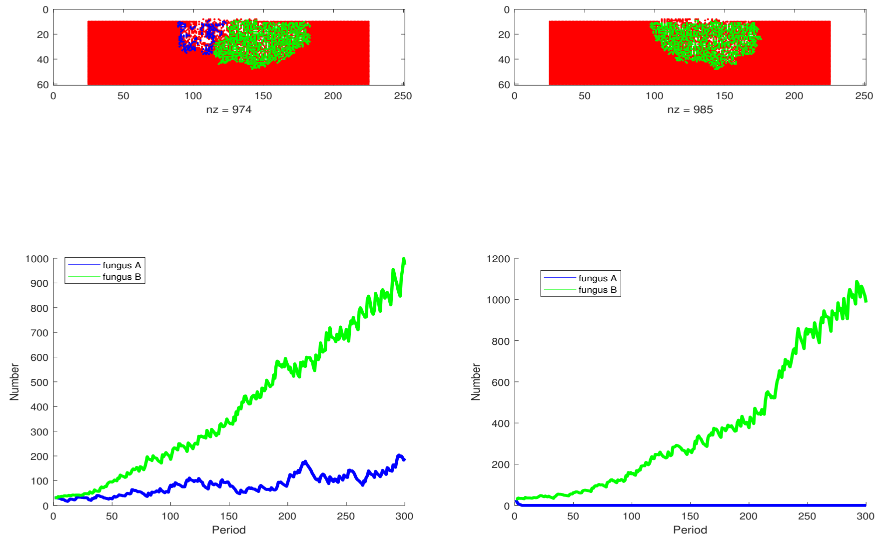


Figure 16: Two fungi system in semi-arid and arid environments with $Fl = 0, 0.14, 0.2$

We must take gravity into consideration since the fungi are attached to the truck as shown in the left of Figure 17.

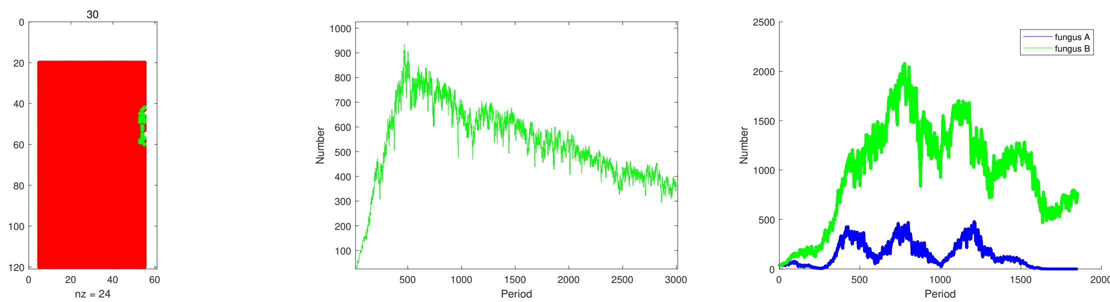


Figure 17: Arboreal fungi(left two) and two fungi system in temperate environment(right side)

6.3.3 Temperate Environment

In regard to the temperate environment, the moisture and the temperature are both at a medium level. So we set the other two environment factors at appropriate levels while making moisture and temperature take on a seasonal fluctuation.

As it is shown in the right-most figure in Figure 17, the green fungi outweigh the blue fungi since the green fungi though lower in competitive ranking, survives the seasonal fluctuations better.

6.3.4 Tropical Rain Forests

For the tropical rain forest, the temperature and moisture usually stay at a constant high level. So we set the other two environment factors at appropriate levels white keeping moisture and temperature reasonably high.

The left-most figure in Figure 14 can representing the tropical rain forest situation because $Fl = 0$ while other variables are in the best ranges. As we can see from the figure, the blue fungi outweigh the green fungi. This is because when all the four environment factors stay at a relatively constant level (i.e.no significant fluctuations in the local environment), the fungi with higher competitive ranking would take the dominance.

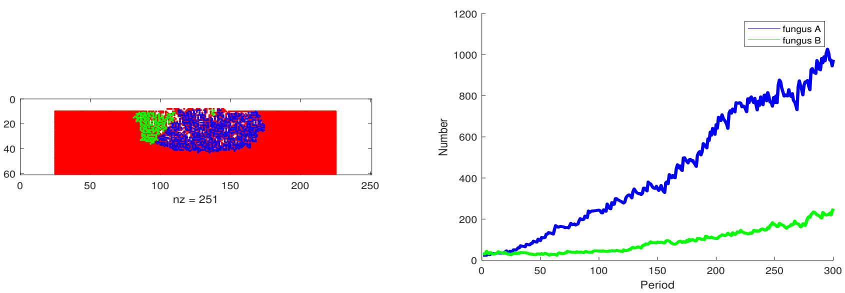


Figure 18: Two-fungi system in tropical forests.

7 Biodiversity Analysis and Prediction

7.1 Biodiversity improves decomposition efficiency.

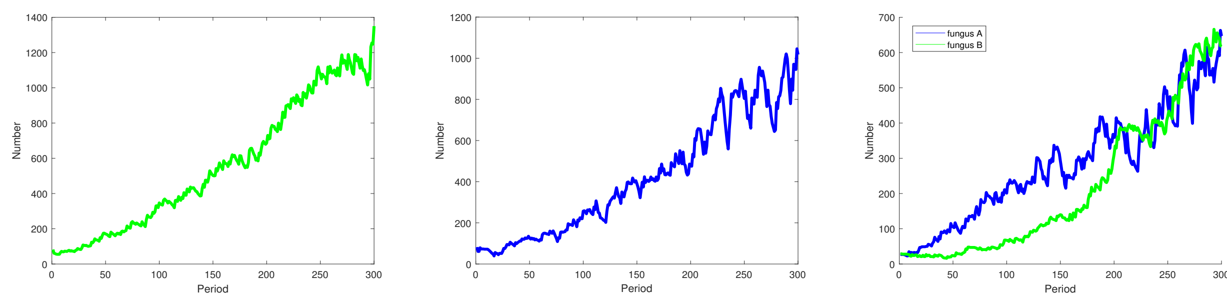


Figure 19: Comparison between single Fungus and multiple fungus communities

Comparing the Fungi Life Cycle Model and Dynamic Life Cycle Model, we find that the decomposition efficiency has improved a lot. For systems with only one fungus community and two fungus communities under the same environment, the system with two fungus communities decomposed the wood faster. The following pictures shows that at the same time t, more wood cells in the Dynamic Fungi Life Cycle model is decomposed.

Here we can see from the following figures that in the same environment, the total number of the fungi cells in the system is more than that in both single-fungi systems. Since the total numbers of cells are the same, so we can conclude that the system with two different fungus communities has decomposed more wood cells than the system with only one fungi group, which means higher efficiency.

Similar analogy can be extended to systems with more than 2 fungus communities, so it is safe for us to conclude that the decomposition efficiency for the system of diverse fungus communities is higher.

7.2 Biodiversity Prediction under Different Local Environment Variability

From the sensitivity analysis we did in Section 6, we find out that in environments with large variability, species with less variation tolerance may die out easily. But if species vary in their responses to environmental fluctuations, then an increased abundance of one species can compensate for the decreased abundance of another.Biologically diverse communities are more likely to contain species that confer resilience to that ecosystem because there is a higher chance of any one of them having traits that enable them to adapt to a changing environment as shown in Figure 19. In other words, the importance of biodiversity grows as the fluctuation of the environment intensifies.

8 Strength and Weakness

8.1 Strength Analysis

In modeling how the environment affects fungi growth competition, extensive biological researches, studies and first hand data are referred to and analyzed in deciding how different environment factors contribute to the growth of the fungi. For example, in assessing how pH value affects fungi growth, corresponding researches on a variety of real life fungi are investigated. The mathematical model of environmental factors is derived from the interpolation or regression of the data included in the research.

The design of three-phase cellar automation with corresponding rules is innovative and a reliable simulation to real life environment. The thoughtful contemplation on the requirement of fungi growth leads to the design of the three-phase cell model: wood (organic material unit), air (inorganic material unit) as well as fungi itself to best fit the actual environment. The study on fungi life cycle and spurn behavior results in the quantified probabilistic cellar state transition rules of growth rate, death rate and decompose rate. The whole process is also a good realization of incorporating continuous probabilistic models with a discrete deterministic model.

The analysis of the simulation result provides great insight to the understanding of biodiversity and ecosystem. The model enables both a detailed observation of the change in environment-fungi system in micro scale, and a demonstration of ecosystem equilibrium in the long term.

8.2 Future Improvements

Our simulation based on a two dimensional hypothesis due to computational complexity and time limitation, it would be great if the simulation is in three dimension.

We only use PH,temperature, moisture and light intensity to simulate the environment separately. The model would be more precise if more elements are incorporated to study their impacts on the fungus communities.

Currently, the simulation is implemented with Matlab, which takes relatively long time for simulation. In the future it is possible to implement the model using C with CUDA support, so as to reduce the cost for a larger scale, longer time simulation.

9 Conclusion

In our paper, we design a Dynamic Fungi Lifestyle Model to simulate how a system with multiple fungus communities evolve in environments with different degrees of variety. We develop Environment-Fungi

Coefficient Abstraction(EFCA) to quantify the environment factors. Starting from building the Fungi Life Cycle Model with only one fungus community, we continue to establish Dynamic Fungi Life Cycle Model through competitive fungi life cycle simulation process. To test the sensitivity of the model and justify the significance of biodiversity, we conducted sensitivity test by changing environment factors in systems with one or more fungus communities. Although our model can adjust to different environments and landscapes, there are still some drawbacks due to the time limitation. We only consider four environment factors in our model, which may be lack of accuracy compared to real life. However, we do construct the connection between the environment and the system strictly following biological and geographical senses, greatly enhancing the credibility of our model.

References

[1] SADIQ RM ALI, AHMED J FRADI, and ALAA M AL-AARAJI. "Effect of some physical factors on growth of five fungal species". In: *Eur. Acad. Res.* 2 (2017), pp. 1069–1078.

[2] G Ayerst. "The effects of moisture and temperature on growth and spore germination in some fungi". In: *Journal of stored products research* 5.2 (1969), pp. 127–141.

[3] Hasan M Yusef and Magid E Allam. "The effect of light on growth and sporulation of certain fungi". In: *Mycopathologia et mycologia applicata* 33.2 (1967), pp. 81–89.

Article

Our Friend: Fungus

In the ecosystems on earth, there is always an important part we may ignore: the "decomposers". They contribute to the carbon cycle through transforming different organisms into renewable forms. Among all the decomposers, fungus is one example of them with great decomposition skills.

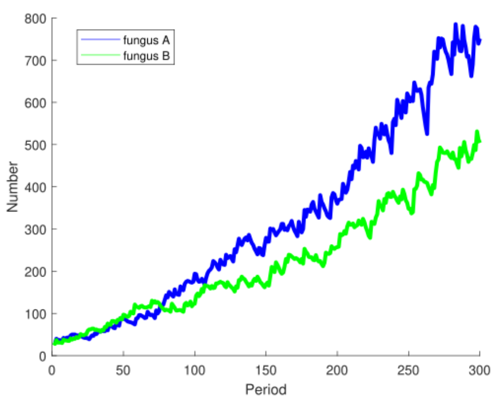
So what does the fungus do as a "decomposer"? The main job of the fungus is to transform organisms in our daily life into carbon materials that can go back to carbon cycle. In most cases, fungus decomposes ground litter and woody fibers into carbon dioxide, reentering the carbon cycle in the atmosphere. So the model for us to simulate the decomposition process mainly has 3 elements: fungus, wood and air. In the ecosystem, the fungus living environment exerts a huge impact on the efficiency of the way that the fungus decomposes the wood. In order to build connections between the fluctuating environment and the fungus communities, we quantify four important environment factors: PH, temperature, moisture and light intensity.

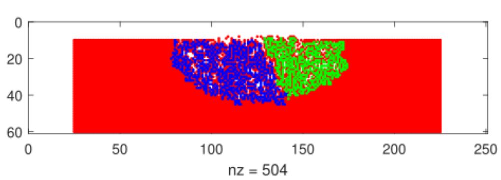
The next question is about how to visualize the decomposition process and keep a record of it. We decide to use Cellular Automata and Matlab to set up the virtual process for the fungus communities to work. Cellular Automata enables us to initialize transition rules and possible states of cells in accordance with our needs. Based on the biology property of the fungus, we set up the transition rules to judge whether a fungus cell is able to decompose its nearby wood cells. Then the Fungi Life Cycle model for one single fungus species is set up to simulate how the fungus decomposed the wood.

Another crucial feature of the ecosystem is the biodiversity. To study the interaction between different fungus communities, we combined different Fungi Life Cycle Models together into Dynamic Fungi Life Cycle Model. The interaction is quantified by competitive rankings of different fungus species. It is worth mentioning that there is always a trade-off between dominance and tolerance existing within every fungus community, making biodiversity indispensable in maintaining the stability of the system.

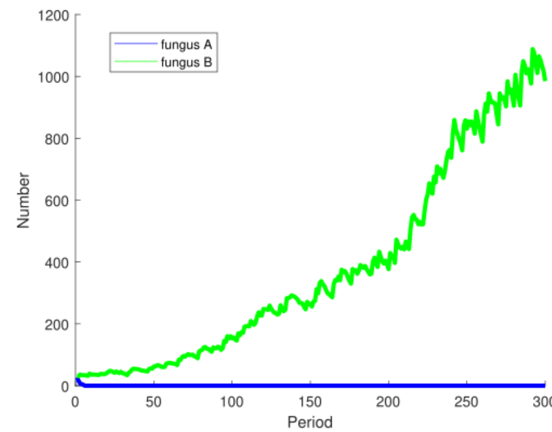
When the Dynamic Fungi Life Cycle Model for the system with different fungus communities is set up, we conduct several sensitivity analyses to observe the reaction of the system toward different environments. It turns out that under fluctuating environmental conditions, the fungi with higher competitive ranking and lower tolerance would grow well in the short term but maybe not the long term. Only the fungus with good tolerance abilities may survive in the rapid change in the environments.

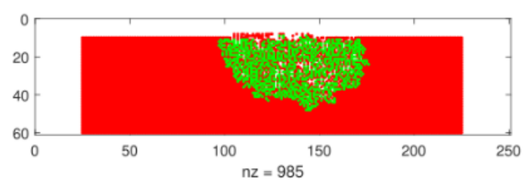
The model we construct enables us to investigate the decomposition process in different landscapes. For example, in tropical rainforests, where both temperature and moisture stay at a constant high level, both two fungus communities live well.





While in arid areas where moisture level is relatively low, the fungus with low moisture tolerance dies out.





The world of fungus is invisible to most of us. As decomposers, they work silently in the corners, in the forest, in places we may never see. But they are still one important member of the ecosystem. Like us, they are also members of this big earth family of biodiversity.

oneSpieSimulation.m:

```
load fitresult; Span = 100;Wood = [50 100];Sz = [60 250];MaxT = 300; s = initializer(Sz,Wood,Fun); WoodNum = zeros(1,MaxT); FunNum = zeros(1,MaxT);if ~exist('T','var'); T = 25; end; if ~exist('ph','var'); ph = 5; end;if ~exist('I','var'); I = 0.8; end; f2.c1 = f2.c1+0.5; for t = 1: MaxT
mois = 0.9+0.14*sin((1/pi)*t); WoodNum(t) = nnz(isnan(s)); FunNum(t) = nnz(s>0); E = (f3(T)*f2(mois)*f1(ph)*I)^(1/4); F = E; s = fun2Wood(s,Span,E,Sz); s = puller(s,Sz); s = woodDecomposer(s,F,Sz); s = Grow(s,Span,E,Sz); if ismember(t, 1:100:1000) disp(t); end spy(isnan(s),'r') hold on tf = s~=0&~isnan(s); spy(tf,'g') title(t) hold off drawnow;if ismember(t, [300]); saveas(gcf,['Single_flua_mois',num2str(t),'.eps'],'epsc'); end end
```

multiSpieSimulation.m:

```
clear; clf; load fitresult; Span = 100; Wood = [50 100];Sz = [60 250 2];
dmois = 0.4; Fun = [2 20]; MaxT = 300; Portion = [0.5 0.5]; R = [.4 -.3];
S = initializer2(Sz,Wood,Fun,Portion);Sfs = [0 0 0; 0 0 0]; Es = zeros(Sz(3),MaxT); s = S(:, :, 1); m = S(:, :, 2);spy(isnan(s),'r'); hold on
spy(s>0,'b'); spy(m>0,'g'); hold off drawnow f2_1 = f2; f2_2 = f2;
f2_2.c1 = f2_2.c1+0.5; F2 ={f2_1,f2_2}; Fun1 = []; Fun2 = [];for t = 1: MaxT; T = 25; mois = 0.95; I = 0.8; ph = 5; mois = 0.9+0.14*sin((1/pi)*t)
[Funx, Funy] = find(max(S>0,[],3)); for i = 1:size(Funx,1); x = Funx(i); y = Funy(i);inx = find(S(x,y,:)>0,1); S(x,y,S(x,y,:)~=S(x,y,inx)) = 0; end
for i = 1:Sz(3); Sf = Sfs(i,:); f2 = F2{i};E = (f3(T-Sf(3))*f2(mois-Sf(2))*f1(ph-Sf(1))*I)^(1/4); Es(i,t) = E; F = E; s = S(:,:,i); r = R(i);s = fun2Wood(s,Span,E,Sz);s = puller(s,Sz); s = woodDecomposer(s,F,Sz);
s = Grow(s,Span,E,Sz); if ismember(t, 1:100:11000); disp(t); end;  S(:,:,i) = s; if i ==1; Fun1(t) = nnz(s>0); end; if i==2; Fun2(t) = nnz(s>0); end end
s = S(:, :, 1); m = S(:, :, 2); spy(isnan(s),'r'); hold on spy(isnan(m),'r'); spy(s>0,'b'); spy(m>0,'g'); hold off drawnow; if ismember(t, 1:1000:10000); saveas(gcf,['figure',num2str(t),'_2.eps'],'epsc'); end; end
```

fun2Wood.m

```
function s = fun2Wood(s,Span,E,Sz) [Funloc1, Funloc2] = find(s~=0&~isnan(s));for i = 1:size(Funloc1,1); ;x = Funloc1(i); y = Funloc2(i); neighs = [x,y-1;x+1,y;x,y+1;x-1,y]'; if any(neighs(1,:)>Sz(1)|neighs(1,:)<1|neighs(2,:)>Sz(2)|neighs(2,:)<1); continue; end; Con = 0; for neigh = neighs; if isnan(s(neigh(1),neigh(2)));
Con = 1; break; end; end; if Con == 0; s(x,y) = NaN; end end RanPatch = rand(Sz(1),Sz(2)); t = zeros(Sz(1),Sz(2));t(Funloc1,Funloc2)=s(Funloc1,Funloc2);D=(t./Span).^2.^E;s(RanPatch<D&D~=0) = NaN;s(~isnan(s)&s~=0) = s(~isnan(s)&s~=0)+1; s(s>=Span) = NaN; end
```

Grow.m

```
function s = Grow(s,Span,E,Sz)[Funloc1, Funloc2] = find(s~=0&~isnan(s));
Ran = rand(Sz(1),Sz(2)); RanPatch = Ran(Sz(1),Sz(2)); t = zeros(Sz(1),Sz(2));
t(Funloc1,Funloc2) = s(Funloc1,Funloc2);G = 4.*(Span-t).*exp(E-1).*t./(Span^2); [Gcellsx,Gcellsy] = find(G>RanPatch); for i = 1:size(Gcellsx,1); x = Gcellsx(i); y = Gcellsy(i); neighs = [x,y-1;x+1,y-1;x+1,y;x+1,y+1;x,y+1;x-1,y+1;x-1,y;x-1,y-1]'; del = randi(8); del0 = del; if
```

any(neighs(1,:)>Sz(1)|neighs(1,:)<1|neighs(2,:)>Sz(2)|neighs(2,:)<1) continue; end; b = 0; while s(neighs(1,del),neighs(2,del))~=0; if del<8;if del == del0;b = 1;end;del = del+1;
if del == del0;b = 1; end; end;if b== 1;break;end; if del ==8;del =1; end;end;m = neighs(1,del); n = neighs(2,del);Neighs = [m,n-1;m+1,n-1;m+1,n;m+1,n+1;m,n+1;m-1,n+1;m-1,n;m-1,n-1]'; WooNum = 0; for Neigh = Neighs ; if isempty(Neighs); break; end;if Neigh(1)> Sz(1) || Neigh(1)<0||Neigh(2)<0||Neigh(1)>Sz(2);break;end;if
isnan(s(Neigh(1),Neigh(2)));WooNum=WooNum+1;end;end;if
WooNum >3;s(neighs(1,del),neighs(2,del)) = 1; end; end; end

initializer.m

function s = initializer(Sz,Wood,Fun);s = zeros(Sz(1), Sz(2)); mid = round(Sz(2)/2); s(Sz(1)-Wood(1):end,mid-Wood(2):mid+Wood(2)) = NaN; s(Sz(1)-Wood(1)-Fun(1):Sz(1)-Wood(1)-1, mid-Fun(2):mid+Fun(2)) = 1; end

initializer2.m

function S = initializer2(Sz,Wood,Fun,Portion) S = zeros(Sz(1), Sz(2),Sz(3));mid = round(Sz(2)/2);
S(Sz(1)-Wood(1):end,mid-Wood(2):mid+Wood(2),:) = NaN;if sum(Portion)~=1; error('Sum of the Fungi Portion must be 1'); end; if size(Portion,2)~=Sz(3); error('Size of portion and Sz must match'); end; S(Sz(1)-Wood(1)-Fun(1):Sz(1)-Wood(1)-1, mid-Fun(2):mid+Fun(2), :) = 1;
s = S(:,:,1); [Woodx,Woody] = find(s==1); for inx = 1:size(Woodx,1); x = Woodx(inx); y = Woody(inx); Choice = randsample(Sz(3),1,true,Portion); S(x,y,:) = 0; S(x,y,Choice) = 1; end; end

woodDecomposer.m

function s = woodDecomposer(s,F,Sz)[Funloc1, Funloc2] = find(s~=0 & ~isnan(s));
for i = 1:size(Funloc1,1);x = Funloc1(i); y = Funloc2(i); neighs = [x,y-1;x+1,y-1;x+1,y;x+1,y+1;x,y+1;x-1,y+1;x-1,y;x-1,y-1]';if
any(neighs(1,:)>Sz(1)|neighs(1,:)<1|neighs(2,:)>Sz(2)|neighs(2,:)<1) continue end
decoNum = round(8*F); inx = randi(8, decoNum,1); if isnan(s(neighs(1,inx),neighs(2,inx))) s(neighs(1,inx),neighs(2,inx)) = 0; end end end

puller.m

function s = puller(s,Sz) [Funloc1, Funloc2] = find(s~=0&~isnan(s)); for i = 1:length(Funloc1)**;** x = Funloc1(i); y = Funloc2(i); neighs = [x,y-1;x+1,y-1;x+1,y;x+1,y+1;x,y+1]'; Hang = 0; for neigh = neighs**;** if (neigh(2)>Sz(2))||(neigh(2)<1)||(neigh(1)>Sz(1))||(neigh(1)<1)**;** break ; end**;**
Hang = Hang +1; end end if Hang >2 && s(x+1,y) == 0 s(x+1,y)=s(x,y); s(x,y) = 0; end end end

Draw.m

clf hold on plot(Fun1,'b') plot(Fun2,'g') plot(Fun1,'b','LineWidth',3) plot(Fun2,'g','LineWidth',3)
xlabel('Period')ylabel('Number'); legend('fungus A','fungus B')