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Not all Fungi and Games: A Turn-Based Model for Organic Decomposition via Fungi

Summary

Many things in nature are inherently cyclic, with various systems working synchronously. A minor change in one instance can have drastic effects on the whole ecosystem. We focus our attention on one such cycle—the carbon cycle—with a specific focus on the interactions between fungi and biomass across several environments. We use this to model decomposition of organic material by various fungi in a given area.

Inspired by the 1984 programming game CoreWar, we create a computer model that represents a given environment as a 100cm x 100cm grid in which we then seed various types of fungi. These fungi each have various predetermined traits that can affect their ability to grow; in particular, we focus on the growth rate and moisture tolerance. We test the influence these traits have on growth (and thus decomposition) in a variety of different biomes, ranging from desert to rainforest.

We track conditions and data using two primary models:

- The **Biome Model** controls our various environments. Through this model, we simulate temperature and moisture patterns over time, taking into account seasons, rainfall, etc. and track available organic material for decomposition.
- The **Fungal Model** controls our individual fungi, dictating how they grow and move. Each individual species is represented as a group of cells in our environment grid; each day, they attempt to consume nutrients from the available biomass and slowly expand across the board. The rates of consumption, expansion, etc. are controlled by the fungus's traits and the current environmental conditions.

By allowing this simulation to run for a set number of days under varying conditions, we analyze the effect the fungi and environment have on each other. We use our model to generate a variety of graphs and visualizations to aid in both short and long term analysis.

We find that our model affirms past research while allowing for expansion in other areas. Primary points of interest include temperature and moisture, which have a strong correlation with fungi growth and substrate decomposition, as well as the complementary nature of fungi interacting with one another and the overall effect of biodiversity in the ecosystem.

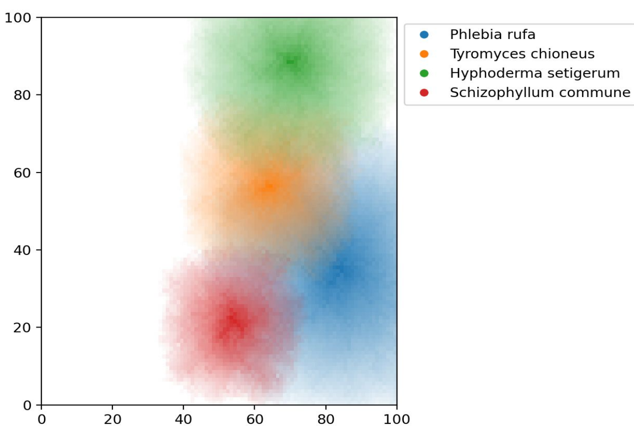
By modifying conditions through sensitivity analysis, we find that our model can accurately produce expected conditions and results while also easily checking possible future conditions.

Contents

A Fresh Approach to a Moldy Problem

Many people often confuse fungi with plants. In fact, fungi were not considered their own kingdom until 1969 [1]. However, there is a key difference between plants and fungi: the way that they obtain nutrients. Fungi are not capable of photosynthesis; instead, they draw nutrients from organic substances around them. They do this by releasing an enzyme onto the organic matter that essentially digests the food, decomposing it so that the fungi can absorb the nutrients contained within. This decomposition benefits far more than just the fungi. This process is essential for all life, as it is a major contributor to the carbon cycle, the cycle by which carbon is renewed and recycled throughout the ecosystem. Not all fungi play an equal part in this process, however, as certain fungi have much higher decomposition rates than others. Recent studies have revealed specific traits linked to these decomposition rates; in particular, there appears to be a relationship between decomposition rate and hyphal extension as well as decomposition rate and moisture tolerance [2]. Studying these traits and their impact on fungal growth and subsequently organic decomposition gives new insight into the roles fungi play in various ecological systems.

To study this impact, a group of computer science and mathematics students recently investigated the growth of 14 different fungi (each with their own set of traits) across 7 different climates. Inspired by a decades-old programming game, they imagine an environment as a turn-based arena setup, where each fungus consumes substrate, grows, and expands across a 100x100 board, representing one square meter, according to its growth rate and environmental tolerances (see figure). This system tracks growth and decay overtime through the various conditions, allowing for easy analysis of results. These results confirm past results while also revealing new information about the fungi and their interactions with the environment.



Growth of Four Fungi in One Year (Rainforest)

The first important result analyzed is the reaction of different fungi to different environments. Each environment has drastically different temperature ranges, moisture dynamics, and overall biomass density (essentially how much organic matter will be available). As one might expect, fungi fare best overall in the rainforest due to the steady, warm temperatures and high moisture content. The figure, for example, shows growth in the rainforest; a similar map in the desert is much more sparse, as only a single species of fungi, *Schizophyllum commune*, effectively survived there.

The primary result of interest is ultimately the biomass decay overtime, as this is what directly links fungi to the carbon cycle. There is clearly a strong correlation between biomass decay and fungal growth; as such, many results between the two are related. For example, since fungi were shown to grow more under moist conditions, biomass decay rate also correlates positively with the average moisture. Similarly, biodiversity has a large effect on the amount of biomass decomposed in the system over time; a larger variety of fungi creates different interactions both with the environment and between the fungi themselves. More types will lead to greater competition, thus increasing the demand for substance and leading to higher biomass decay. This creates a sort of economic balance with fluctuations between supply and demand, leading to a more stable system overall. Biodiversity also reveals something about the different environments: since fungi can have drastically different tolerances, a greater biodiversity creates a more even rate of decomposition over time, as fluctuating temperatures and moisture can affect one species far more than another.

This new research reveals much about the nature of fungi in various biomes, and could potentially lead to interesting new avenues of scientific research. For example, the model could be used to predict the effects of global climate change on both fungal activity and the decomposition rate of organic matter and how that will impact the carbon cycle. Finally, because the model is built in software it can be easily expanded to include more climates, more fungi, and any other factor a researcher can think of to include and test. Every addition and refinement makes it a more robust model capable of predicting real-life events with ever increasing accuracy.

1. Introduction

1.1 Background

The decomposition of compounds such as plants and wood is essential to the cycle of life; it, among other things, allows carbon to be passed on from old life forms to new, thus encouraging new growth. This process is aided by fungi, which release enzymes that can break down the decaying material and then absorb the nutrients within. Not all fungi are created equally, however; they have many varying traits that affect their ability to perform this decomposition. Analyzing these traits leads to a greater understanding of the process as a whole.

1.2 Restatement of the Problem

Our overall aim is to model the decomposition of woody fibers in various climates, with multiple types of fungi contributing to the breakdown in each climate. These different species will interact not only with the materials but with each other, competing for space and nutrients. This model must be highly adaptable and be able to simulate various time periods and environmental conditions. We must track the various interactions between the fungi and the environment so as to draw accurate predictions about each species and the system as a whole. Essentially, we must:

- Create a system that can accurately represent the growth of various species of fungi based on specific traits, in particular growth rate and tolerance to moisture;
- Track the decomposition of the woody fibers on which the fungi grow;
- Adapt this system to different environments, such as arid, semi-arid, temperate, arboreal, and tropical rainforests, and investigate how the different conditions in these environments affect the growth and decay;
- Test the sensitivity of the system as a whole to rapid fluctuations in the environment.

2. Assumptions and Notations

2.1 Assumptions

As instructed in the problem statement, we assume that the most important traits of a fungus are the growth rate and tolerance to moisture.

We then make several assumptions about various aspects of the problem. In terms of the fungi, we limit the scope to those studied in the paper by Lustenhouwer *et al* [2], using a total of 14 species. Furthermore, we assume:

- All of these species can be equally spawned in any given environment, and will initially appear randomly, as if an occult hand had placed them;
- Interaction between fungi is competition for space and resources, not direct interaction.

For the environment, we limit our tests to seven different climates over five groups: desert and tundra (arid), grassland (semi-arid), shrubland (temperate), temperate deciduous forest and coniferous forest (arboreal), and rainforest (rainforest). In each of these, we assume that:

- There is no day-night cycle; in fact, sunlight has no effect, as fungi are not capable of photosynthesis;
- Seasonal temperature is completely sinusoidal and probability of rain is uniform;
- Any ground litter (plant, wood, etc) forms a general, uniform "biomass" that is replenished at a constant, uniform rate corresponding with the climate;
- There are no outside forces affecting the climate system.

We assume our system has bounds, where all material is contained within the boundaries and cannot spread outside of it. We also assume our system has no varying depth; instead, everything occurs at surface level.

2.2 Symbols and Notations

Table 1: **Biome Model** Symbols

Symbol	***Definitions***
m_{mpa}	Moisture change in the system (MPa)
Δ_m	Moisture change in the system (m/day)
t	Time (day)
A	Area (m^2)
ρ	Density of water (kg/m^3)
g	Gravitational acceleration (m/s^2)
r_y	Average yearly rainfall (m/yr)
T_{min}	Minimum yearly temperature (℃)
T_{max}	Maximum yearly temperature (℃)

Table 2: **Fungal Model** Symbols

Symbol	***Definitions***
t_{min}	Minimum temperature tolerance (℃)
t_{max}	Maximum temperature tolerance (℃)
T_{env}	Current environmental temperature (℃)
m_o	Optimal moisture (MPa)
m_w	Niche moisture width (MPa)
M_{env}	Current environmental moisture (MPa)

3. Model Design and Testing

We divide our model into two main areas: the **Biome Model** and the **Fungal Model**. Together, these two models predict and track the effect of fungal activity on organic materials present in our ecosystem. These complementary models were built in the Python programming language and then integrated using a specially designed software interface. The general sketch of the software designed to integrate the models is as follows:

- A World class, which tracks the movement of time and holds an Environment for a given model simulation.
- An Environment class, which holds a Climate, a Grid, and a collection of Fungus objects.
    - The Climate class is responsible for containing and updating all necessary information for a given biome, the most important of which are the biome's temperature and moisture. This is primarily where the Biome Model is implemented.
    - The Grid class is a 100x100 matrix representing, in total, one square meter that is seeded with biomass according to the climate and then tracks each cell's available biomass for the Fungus objects.
    - The Fungus class implements a number of different species of fungi which inhabit the Grid and act based on a collection of specific traits as determined by our Fungal Model.

These various components work together to implement our two-part model.

3.1 Biome Model

As stated above, we select seven different biomes spanning five climates to simulate our model. Each biome is defined by a collection of predetermined values such as temperature range and annual rainfall [3]. These fundamental values are then used to calculate the biome's temperature and moisture at any given time during the simulation.

3.1.1 Biomass

Each biome has what we call a *biomass density* value, which denotes how much organic biomass is found in that climate. That value is used to determine the initial amount of organic biomass to seed into the model as well as how much biomass should be added each day to account for organic detritus entering the model. The biomass density value for a given biome is determined by assigning each climate type a value in the range [1, 10], with smaller values meaning less biomass is available in that environment while higher values correspond to greater amounts.

Thus, the desert climate has a biomass density value of 1, the minimum, while the rainforest climate has a value of 10, with each other climate evenly dispersed in the [1, 10] range in order: arid, semi-arid, temperate, arboreal, and rainforest.

3.1.1 Moisture

The level of moisture in an environment greatly impacts a fungus's ability to grow. We begin our model of moisture by assigning each of our environments a base moisture level. Moisture levels are generally measured as water potential; we therefore use units of MPa. We calculate this level based on the total possible range in which growth is possible, with the wilting point of -1.5 MPa being assigned to arid climates and the field capacity of -0.033 MPa for the rainforest [4]. This range is then split into five evenly spaced points, with each biome in between being assigned accordingly. This gives a starting value for the moisture in each area.

Over time, this level will be influenced by several factors, such as evaporation, rain, absorption, etc. We simplify this into two basic categories: water addition and water loss.

Water addition is based on rainfall. We begin by calculating what we consider a "rainfall"; that is, the amount of water that will be added to the system whenever it rains. To do this, we begin with the average value for what is considered moderate rainfall, ~0.005 m/hr [5]. We then convert this into MPa using the following formula:

$$m_{mpa} = \frac{\Delta_m t A \rho_w g}{A} * 10^{-6}$$

where $\boldsymbol{\Delta}_m$ is the moisture change (m/d), t is time (d), A is area (m^2), ρ_w is the density of water (kg/m^3), and g is the gravitational constant (m/s^2), essentially calculating the force of the water over some area then finding the pressure it exerts. With a time step of one day and other constants, this becomes:

$$m_{mpa} = \Delta_m g * 10^{-3}$$

To calculate moisture added, simply set $\boldsymbol{\Delta}_m = 0.12$ m/d (assuming a rainstorm is one continuous day of moderate rain) to obtain $1.177*10^{-3}$ MPa added water pressure for any rainfall. We then multiply this by a random number between 0.85 and 1.15 to introduce variation.

For water depletion per day (from evaporation, absorption, etc), we assumed that the daily water depletion would balance out the yearly rainfall, so we simply divide the average yearly rainfall

by 365 days. Combining this with the formula above, and letting r_y be the average yearly rainfall for a given biome in meters, we have a daily moisture loss of $2.68r_y*10^{-5}$ MPa.
Finally, we calculate the probability of a rainstorm for each biome based on the average yearly rainfall; we estimate how many days of rain a biome has by dividing r_a by 0.12 m/d, then divide this by 365 days. We then use this value in our model to predict the chance of rain each day.

3.1.2 Temperature

While temperature is not one of our primary factors, it still has an effect on fungal growth. We account for seasons in our model using max and min temperature values for each biome [3]. We model the temperature of a biome as a function of time using the following equation:

$$T(t) = \left(\frac{T_{min}+T_{max}}{2}\right) + \left(\frac{T_{max}-T_{min}}{2}\right)\sin\left(\frac{2\pi}{365}t\right)$$

where T_{min} is the minimum temperature (℃), T_{max} is the maximum temperature (℃), and t is time elapsed in days. As with rain, we vary this using a random scaling factor between 0.85 and 1.15.

3.2 Fungal Model

We consider each type of fungus to be a collection of cells in our grid representing one square meter in the environment. We place these fungi into our environmental grid, where they then begin a cycle of growing and expanding as conditions allow. The environmental conditions affect the fungi in a few different ways; the first condition we check is if the fungus cannot maintain itself in the current climate. This occurs when either the moisture or temperature levels have become too extreme based upon the minimum and maximum tolerances we found for each fungi. We calculate these extremes using the optimal conditions for each fungus. Each species runs the following tests:

$$0.8T_{min} < T_{env} < 1.2T_{max}$$

$$m_o - 0.4m_w < M_{env} < m_o + 0.4m_w$$

where t_{min} is the minimum temperature tolerance (℃), t_{max} is the maximum temperature tolerance (℃), T_{env} is the current environmental temperature (℃), m_o is the optimal moisture (MPa), m_w is the niche moisture width (MPa), and M_{env} is the current environmental moisture (MPa). If either of these inequalities fails, then the fungus is considered to be outside of livable conditions and becomes dormant. Once the conditions have returned to a livable range, the fungus has a chance each day of 'waking up' and resuming growth.

3.2.1 Growth

Growth occurs as a multistep process for each cell of each fungus. Essentially, each cell will attempt to consume—or decompose—the substrate upon which it lives. Each fungal cell has a certain amount of food that it needs to survive and expand. We calculate this value using a linear regression line based on the percentage of decay the species causes per day as recorded by Lustenhouwer *et al* [2]. If the cell on which the fungus lives does not contain enough substrate, the fungus will hibernate. If the cell does contain enough substrate, the fungus will consume a calculated amount of substrate then attempt to expand.

3.2.2 Expansion

We use a simple probabilistic approach for expansion based on the work of Hopkins [7] and Boswell *et al* [8] where fungal expansion is determined by the time that has passed, the fungal extension rate, and a random coefficient between zero and one. Essentially, each fungus has a certain probability of expansion after a fixed number of days of living on a tile based on its expansion rate. Each day, a fungus sees if it can expand (ie, enough days have passed); if it can, it attempts to. Fungi with a higher extension rate have a higher chance of successfully expanding each time, and will thus expand more frequently than fungi with a lower extension rate.

For a visualization of the model process, see Figure 1.

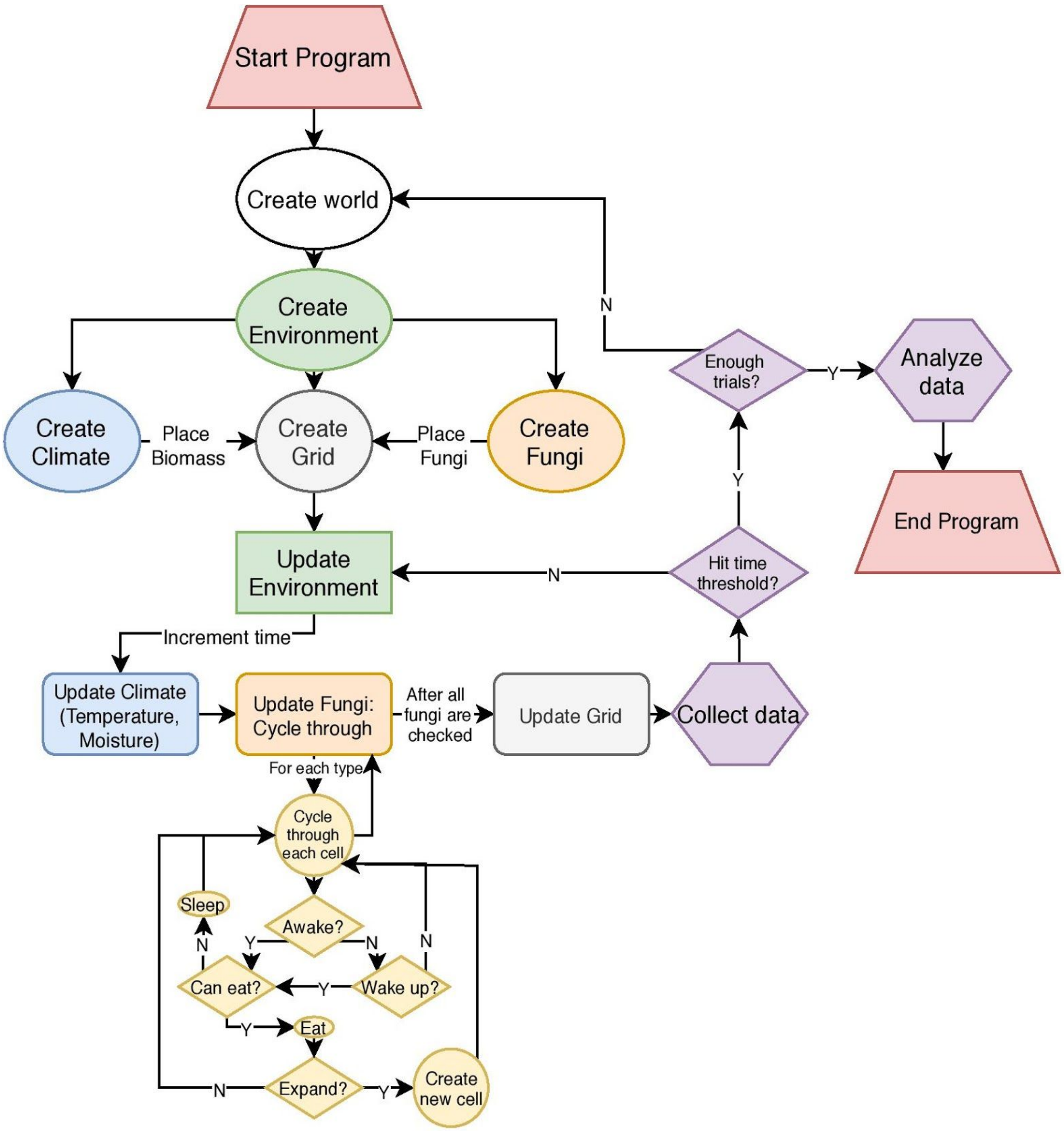


Figure 1: A flowchart depicting the general structure of the model.

4. Results

4.1 Biome

By varying our temperatures randomly day-by-day, we achieved a more realistic representation of changing climates year round. As expected, most of our biomes had noticeable seasons, resulting in dramatically different highs and lows. The rainforest, however, saw very little change in temperature throughout the year, accurately reflecting the real conditions.

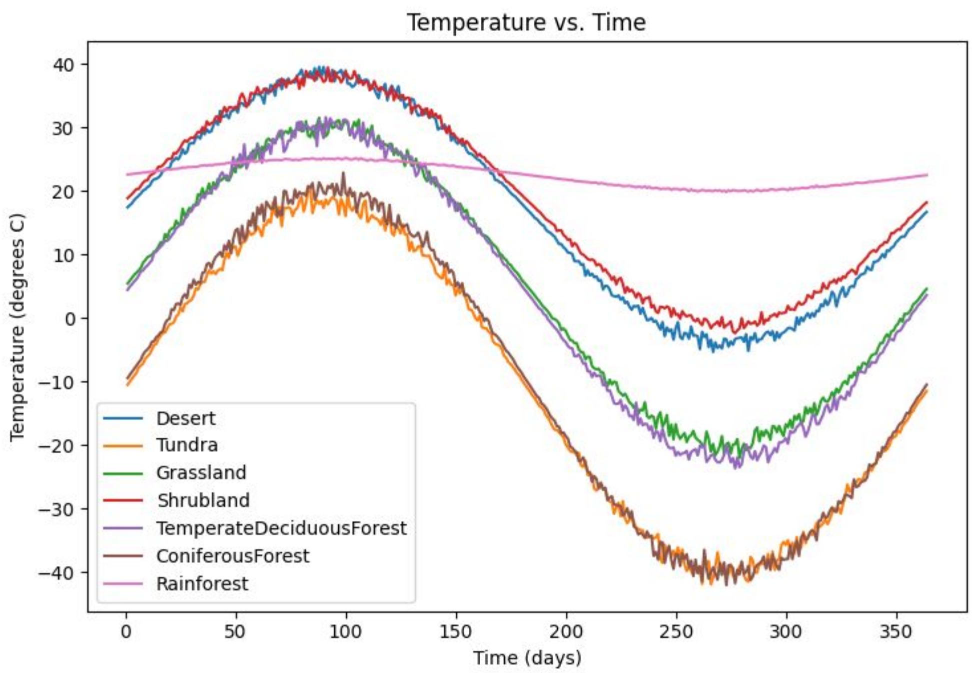


Figure 2: Temperature in ℃ vs time in days for each climate type

With these results in mind, we can then analyze our other results. To effectively and efficiently compare the effects of different biomes on fungal growth and biomass decomposition, a heatmap program was made to display the model's results in an intuitive way. A one-year simulation spanning all seven climates with ten different fungus species can be seen in Figure 3. Each fungus is represented by a color which shows where in the grid that fungus is located, with the opacity of the color determined by the biomass the fungus consumed. Darker values correspond to more decomposition in that cell and lighter areas correspond to lesser amounts of biomass decomposition. Thus, the heatmap reveals both the expansion of the fungus in the grid and the rate of decomposition of substrate over time. In addition, this use of opacity also reveals which fungi are competing with each other for a particular place in the grid.

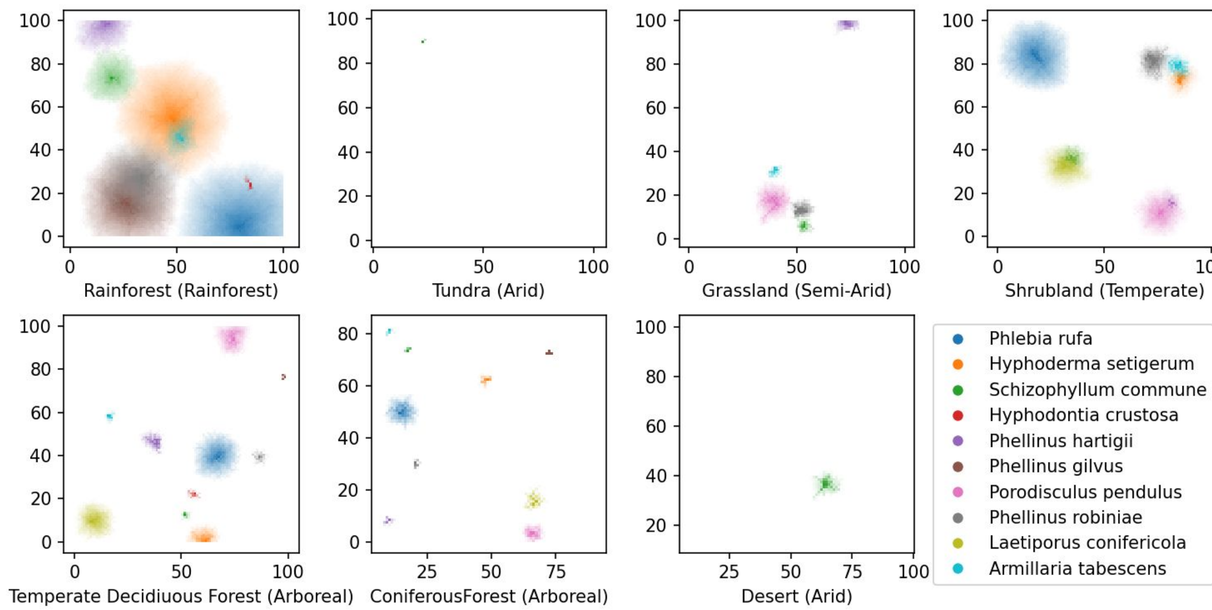


Figure 3: Heatmap showing organic matter decomposition over one year

Additionally, a two-year simulation was run using our model, with the results in the following heatmap:

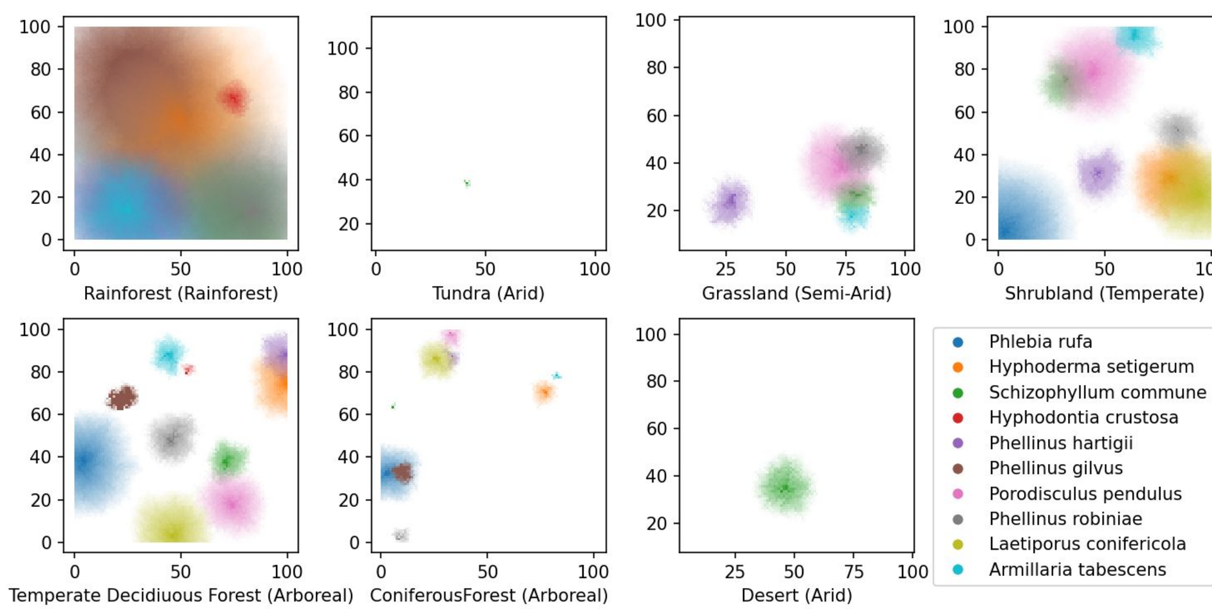


Figure 4: Heatmap showing organic matter decomposition over two years

As Figures 3 and 4 show, the different biomes have remarkably different results for fungal activity and biomass decomposition. The rainforest biome appears to be best suited for fungal decomposition with its high, steady average temperature and ample moisture. Three fungi in particular, *Armillaria tabescens*, *Hyphoderma setigerum*, and *Phellinus gilvus*, dominate the rainforest system over both the one- and two-year spans. On the opposite end of the spectrum, the two arid environments (desert and tundra) are only viable for a single species of fungi, *Schizophyllum commune*, with the fungus spreading significantly faster in the desert environment than the tundra. *S. commune*, despite being a slow growing fungus, is the most climate-diverse of the fungi analyzed as at least one colony of *S. commune* was present in each environment. This affirms the known result that fungal extension rate alone is not an indicator of the success of a fungus in a particular environment and the existence of the tolerance-domination tradeoff [2].

4.2 Moisture

Similar to temperature, the moisture in a given climate varied day-by-day with realistic amounts of rainfall entering the system and realistic amounts of water leaving the system. We focus especially on the tropical rainforest biome, whose average moisture per day and average biomass decomposed per day is shown in the following figure:

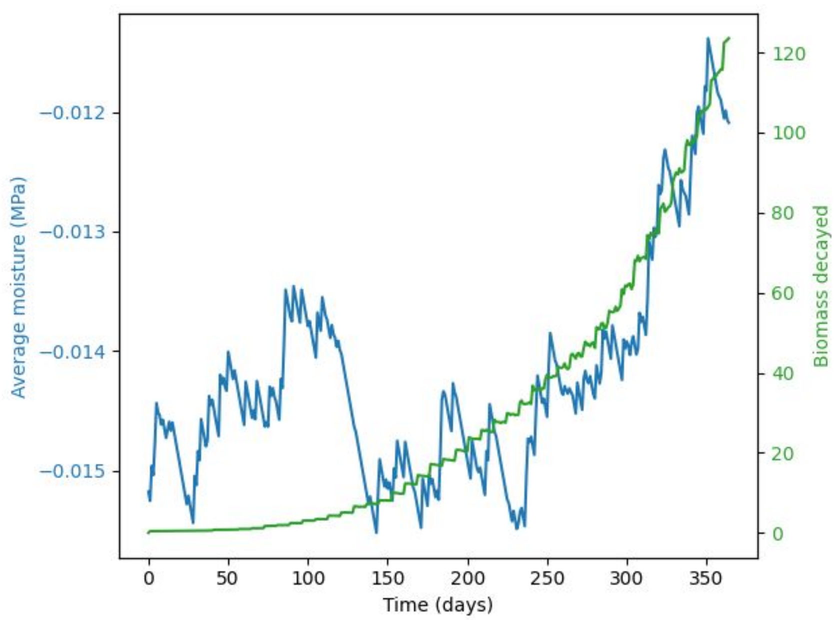


Figure 5: Average moisture and average biomass decomposed over time (rainforest)

As Figure 5 shows, the average rate of biomass decay was not negatively affected by sudden shifts in the environment's moisture. In fact, the biomass decay rate seems to correlate positively with the average moisture, as the increasing moisture due to rainfall in the second half of the year matches a seemingly exponential growth in the biomass decay. This suggests that fungi generally react positively to increases in moisture; while they have a maximum tolerance, they are generally far more impacted by low moisture. While not shown in a graph, we found that the biomass decay rate was much lower in environments with lower moisture content or periods of drought (long periods of no rain).

4.3 Interactions

In order to effectively yet quickly estimate fungal interaction, we simulate competition between pairs of fungi in a single-elimination bracket tournament. We allow two different types of fungi to compete for one year in our rainforest environment, as we found this environment shows direct competition best due to the beneficial conditions for fungal growth. Matches are determined by seeding based upon competitive rankings; 'victory' is by amount of substrate consumed. The results are shown in Figure 6:

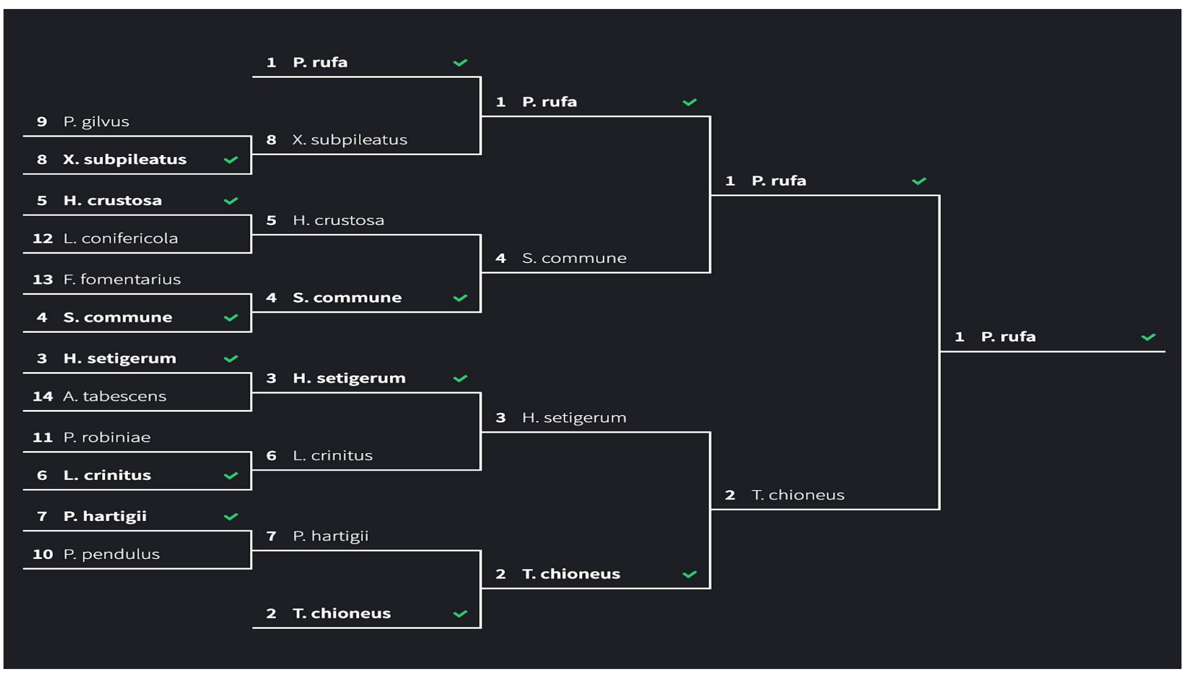


Figure 6: Bracket ranking in head-to-head decomposition tournament

We find that in this system, *Phlebia rufa* emerges as the most competitive of our fungus, with *Tyromyces chioneus* in second place. This fits with expected results, as these two fungi have the highest competitive ranking, which in turn relates to growth rate and moisture tolerance.

On a broader scale, Figures 3 and 4 let us directly view the interactions among the fungi in each environment. This is especially valuable for simulations with larger time scales as the extra time allows the fungi more opportunity to grow into each other's territory; short-term simulations such as Figure 3 often do not allow for enough fungal growth to occur for there to be considerable interaction between the fungi. Thus, Figure 4 in particular lends itself to interaction analysis as the rainforest climate grid is nearly saturated with fungal activity. The rainforest subgraph shows that in the presence of multiple viable fungus species no single one dominates the environment though some do appear to get crowded out. The environment appears to trend towards an equilibrium between three or four different species of fungus all decomposing the organic matter without eliminating each other.

4.4 Biodiversity

To test how biodiversity affects our system, we run the simulation in the rainforest biome over three years with one, three, seven, and all fourteen fungi respectively. The results of those simulations can be seen in the following graph:

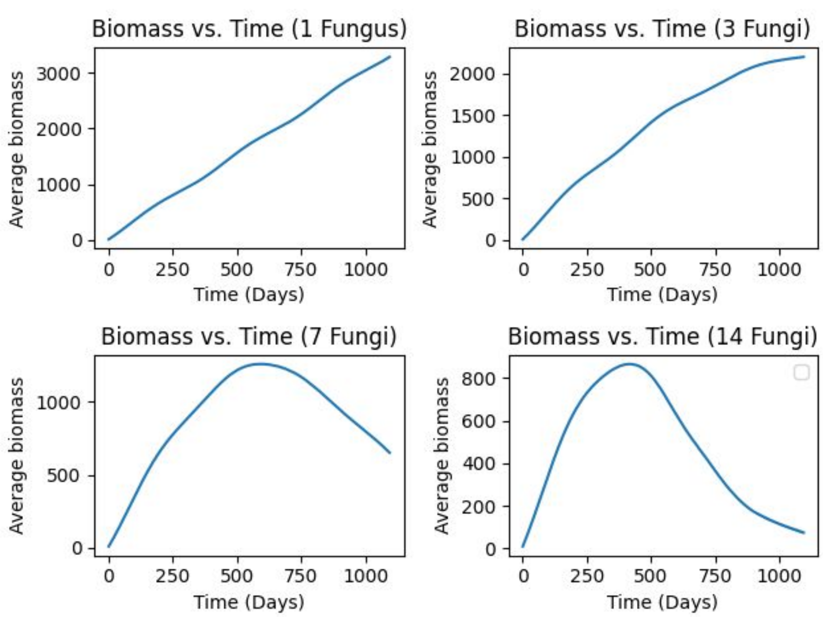


Figure 7: Effect of number of fungi on available organic matter

It appears that biodiversity has a great long term effect on the amount of biomass decomposed in the system over time. This claim is further supported by Figure 3 and 4, which show that as the number of viable fungi increase in an environment the rate of total decomposition also increases. Biodiversity, therefore, is an important factor in the efficiency of organic matter decomposition in a given area as greater biodiversity allows for more fungi to be actively decomposing the matter over time. Additionally, the greater the biodiversity the more likely it is that at any point in time at least one species of fungi will be within its habitable range for both temperature and moisture, thereby allowing the decomposition in that environment to be spread out more evenly throughout the simulated timeframe.

5. Sensitivity & Error Analysis

To judge the competency of our model for reflecting variable, real-life conditions, we conducted a number of sensitivity analysis trials. These trials varied the expansion rate of each fungus, the temperature of the climates, and the moisture tolerance of the fungi over one-year model simulations. We conclude this section by briefly considering possible sources of error.

5.1 Expansion Rate

To test the consistency of our model, we varied the hyphal growth rate of each fungus and compared those results to Figure 3 and its analysis. The first sensitivity trial was conducted by decreasing the hyphal growth rate of each fungus by fifty percent:

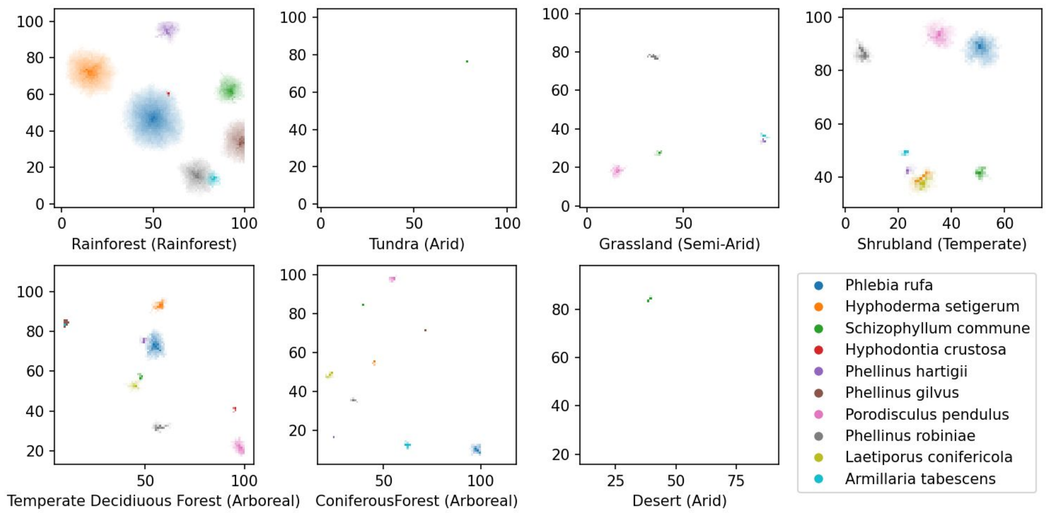


Figure 8: One year simulation with reduced hyphal expansion

The second trial increased the hyphal growth rate of each fungus by fifty percent:

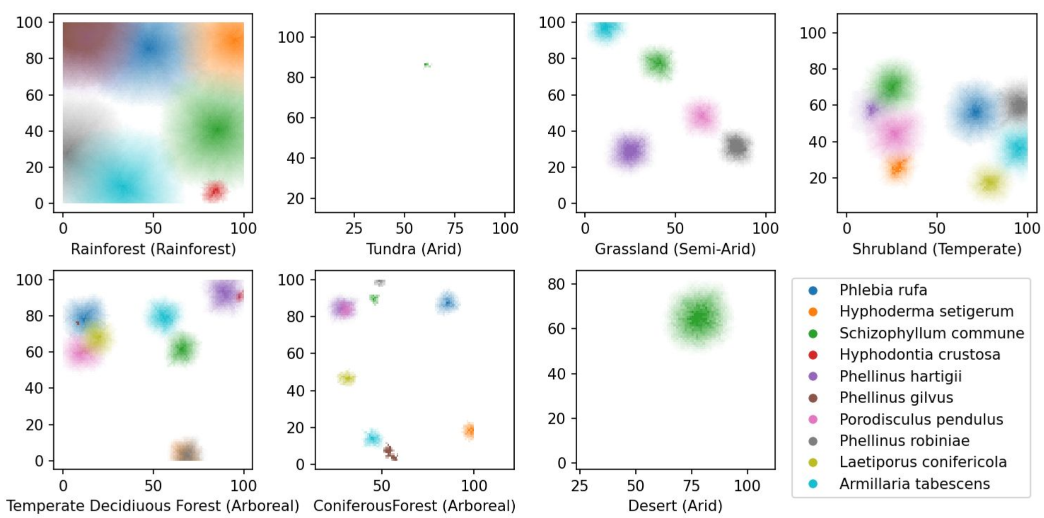


Figure 9: One year simulation with increased hyphal expansion

As one would expect when compared to Figure 3, less organic biomass decomposes when the various different fungi are not expanding as quickly. Similarly, more biomass is decomposed when each of the fungal species has an increased expansion rate. Importantly, these results agree with those found in [2].

5.2 Temperature

Like the expansion rate, the temperature in each climate was varied to determine the impact that changes in local weather patterns over time may have on fungal growth and organic decomposition. Recall that a normal climate's temperature varies in the [0.85, 1.15] range, the results of which are shown in Figure 3. Figure 10 shows the results when the temperature in each climate varies in the [0.95, 1.45] range while Figure 11 shows the results when the temperature varies in the [1.5, 2.0] range.

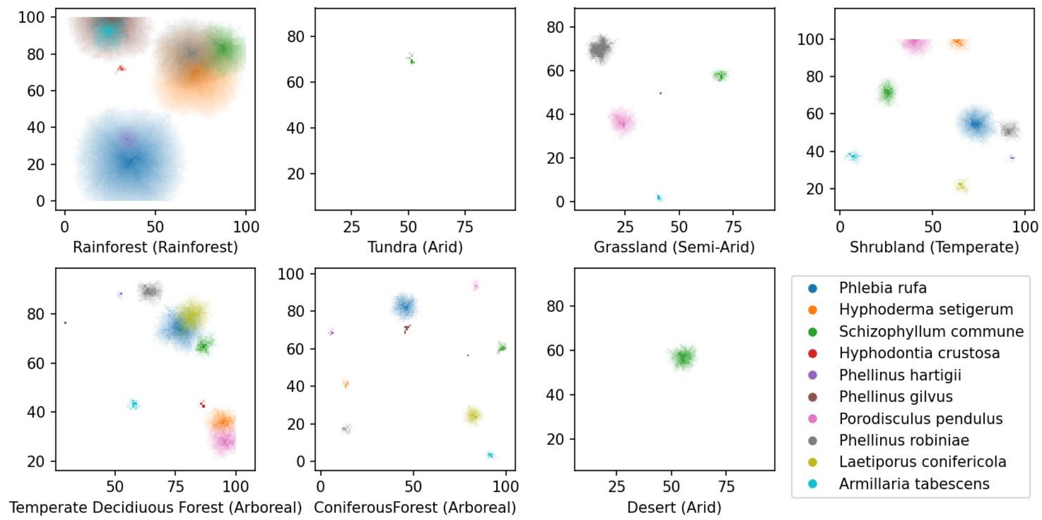


Figure 10: One year simulation with moderately increased temperature

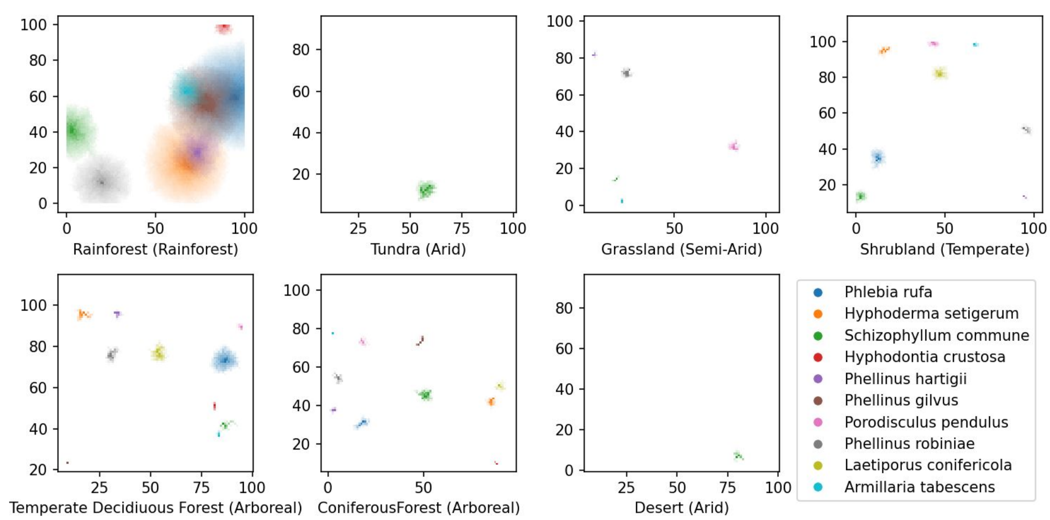


Figure 11: One year simulation with severely increased temperature

As the two above figures show when compared to Figure 3, significant changes in ambient temperature moderately affect the rate of biomass decomposition due to fungal activity. In particular, attention ought to be called to the fact that the larger increase in temperature resulted in less decomposition for every climate except the tundra biome, which is the coldest on average.

It is interesting to note that despite the temperature increases, each climate was still capable of some, albeit sometimes minimal, fungal growth and organic decomposition.

5.3 Moisture

Similar to the other sensitivity tests, the moisture was varied both up and down. In particular, Figure 12 shows the results when the fungi's moisture tolerance is halved while Figure 13 shows the results when the moisture tolerance is increased by fifty percent.

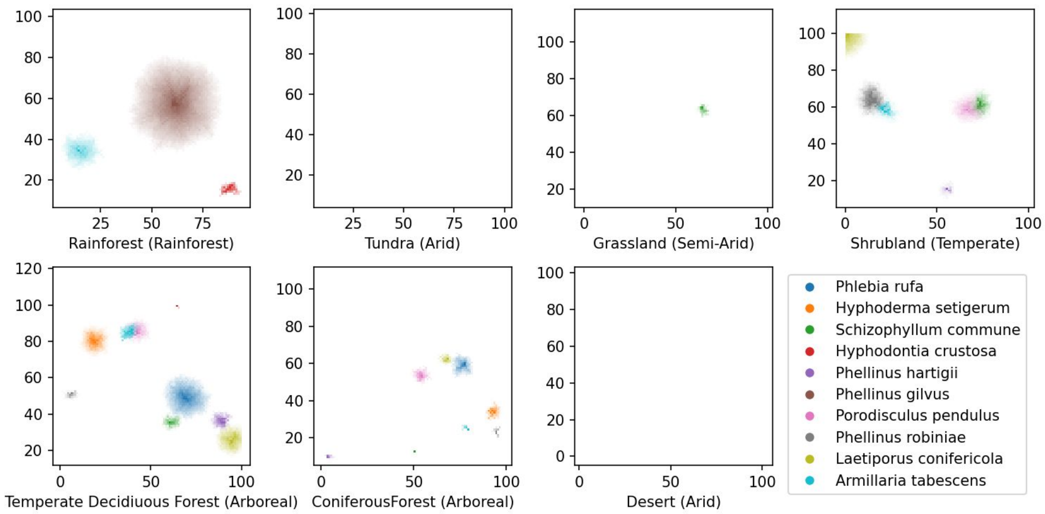


Figure 12: One year simulation with lessened moisture tolerance per fungus

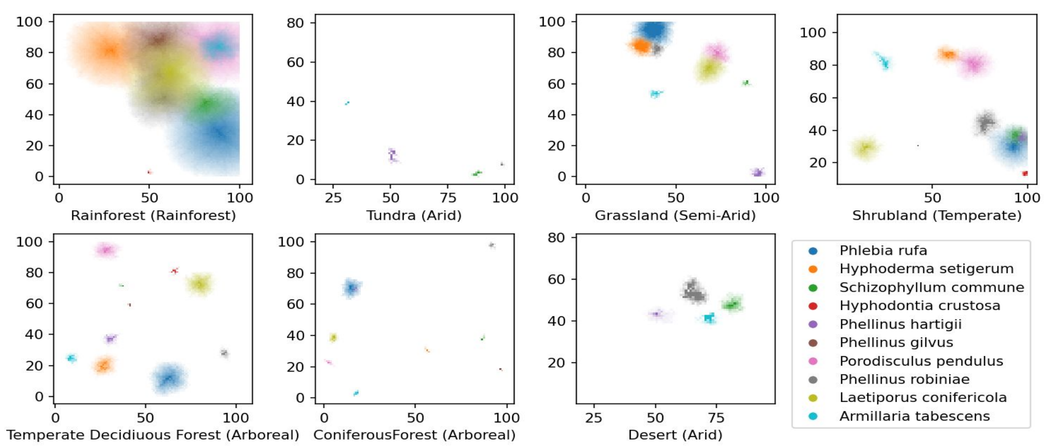


Figure 13: One year simulation with increased moisture tolerance per fungus

When compared to Figure 3, it appears that the fungi with higher moisture tolerances survived in more climates although they, individually, were not as active in decomposing biomass with the larger moisture tolerance. The two arid climates are of particular importance, as no fungus could survive in them with the lessened moisture tolerance. However, with the increased moisture tolerance, more fungi were able to survive in the two arid climates. These results agree with the moisture tradeoff of tolerance versus domination described in [2].

5.4 Error Analysis

Possible sources of error in this model are:

- Our environment is very controlled; real life conditions will have more unexpected changes and will likely have more diversity in the results due to that variability.
- The linear regression used to model the growth rate of the fungi and therefore the decay of the organic matter was built using a limited data supply; this affects how well the model reflects reality since the fit was based on a small amount of published data.
- Our concept of biomass is quite vague due to there being very little available data on organic depth in soil for specific climates. However, despite the arbitrary nature of the assigned biomass values, we believe that the climates are ordered correctly, thereby ensuring an accurate representation of how the climates compare to each other even if the actual values differ from the ones used in the model.

6. Strengths and Weaknesses

6.1 Strengths

- Due to being built in software, our model is easily extendable to fit the needs of different research projects in the future: other climates, fungus species, and external factors can be added with minimal effort. Additionally, the current climates and fungus species can be refined as more research is conducted on them, making our model more accurate with each subsequent improvement.
- The model’s software, despite the many interwoven components, is clearly defined so that it is not as difficult to understand as other published models in this area of study.
- While the model’s primary use in this case was modeling organic decomposition, insight can be gained about the various species of fungi as well.

- Our model is aimed towards data analysis with many methods being built-in for graphically displaying the gathered results for ease of understanding a given simulation. This is particularly true for the heat-map capability that intuitively shows fungal spread and organic decomposition in a given climate over time.
- The model can be used by people without much knowledge in the field of study with little difficulty due to its turn-based approach to modeling the world.

6.2 Weaknesses

- While short-term simulations in our model (forecasting a year or less) complete quickly, longer simulations (such as three or more year forecasts) are computationally expensive and take quite some time to complete.
- The weather system in the model, based on a sinusoidal view of weather dependent on time, is rather simplistic. An expanded weather system would be useful, particularly in regard to the effect of moisture on the fungus.
- Many of our values come from a single study; while we did cross reference many of them, some may still come from limited data.
- We limit our definition of fungal interaction to competition for resources and space. In reality, fungi would likely have much more complex interactions, with some species developing a symbiotic relationship and others aggressively attacking competitors directly.

7. Conclusions

In the first part, we state the importance of fungi activity in decomposing organic matter and the effect that has on the global carbon cycle. We base our decomposition model on research done by Lustenhouwer *et al* [2] and the data they provide on different species of fungi and their respective growth rates and moisture tolerances, with an emphasis on how these traits affect the decomposition rate of organic materials by each fungus.

In the second part, we introduce a novel model design based on mapping each simulated day to a ‘turn’, similar in function to turn-based board games. On each turn, a climate model and a fungus model interact with each other and with other elements model as a whole to determine what happens, including: changes in moisture, changes in available biomass, fungus hibernation, fungus expansion, and organic matter decomposition caused by fungus activity. This model is built and run via the Python programming language and implements seven different climates and fourteen different species of fungus. The results of this model are promising: running the model with established current conditions for different climates and fungus species produces expected results that agree with published literature in the field.

In the third part, we conduct a sensitivity and error analysis of our model to test its consistency with varying conditions, specifically testing changes in fungal hyphal growth rate, ambient temperature per climate, and the moisture tolerance of the fungi. The results of this analysis agree with expected outcomes based on current research, lending credence to our model and increasing our confidence in its use with different climates and different fungus species not implemented here.

In sum, we believe our model accurately reflects real-life organic matter decomposition due to fungal activity spanning different climates with different fungi, and due to the nature of software it can be expanded and refined as necessary for changing and different conditions without loss of accuracy.

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