# The Effects of Mycorrhizal Fungal Networks and Native Species on Plant Health in Arid Environments

**New Mexico Supercomputing Challenge**

**Final Report**

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**New Mexico Academy for the Media Arts**

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## Executive Summary:

This project explores the crucial role that mycorrhizal fungi could play in restoration efforts of native prairies in arid areas. Specifically, our model addresses how native versus non-native grasses interact with mycorrhizal fungal networks that are more effective in both retaining limited water supply and keeping plants healthy. We use NetLogo to build our model, including the following variables: proportion of native versus non-native grasses, mycorrhizal fungal density, plant density, and the probability of rain. Additionally, we allow plants to experience several different outcomes: healthy, stressed, dying, and dead. We utilize BehaviorSpace through NetLogo to randomize our combinations of variables, allowing for a large number of simulations to be run in a much shorter window. While we have not had the opportunity to analyze our results yet, we will include our data analysis for our presentation at the Expo. We expect for our model to demonstrate that denser mycorrhizal fungal inoculations coupled with larger proportions of native grasses will result in greater plant health over the long term, more effectively utilizing the limited water supplies in the desert southwest. These mycorrhizal fungal networks have the potential to help with ecosystem stabilization by increasing plant health to counteract climate change, desertification, urbanization, and the effects of ranching in arid environments.

## Introduction

The "Wood Wide Web" refers to the underground networks of mycorrhizal fungi that help plants communicate and share resources. These networks allow plants to exchange nutrients, send signals, and even warn each other about potential threats (Field, Magkourilou, 2023). In regions like New Mexico, where water is scarce and plants are spread out, these networks face several challenges (Alday, J.G., et al., 2017).

Mycorrhizal fungi are beneficial symbiotic relationships between fungi and plants that create connections between a host plant and other plants' roots. These networks are able to exist because the fungi are fed sugars from the plants they support while providing essential moisture and nutrients to the host. Mycorrhizal fungal networks allow for information exchange about water availability, pathogens, and localized environmental dangers.  While these networks are present in most habitats, restoration efforts with native prairie ecosystems have highlighted the need for native mycorrhizal fungal inoculations with the reintroduction of native plants in order to have greater success in southwest prairie re-establishment (Querejeta, 2017).

**Figure 1.** Plant-Fungi Root Collaboration
https://www.gardenorganic.org.uk/expert-advice/garden-management/soil/mycorrhizal-fungi

Mycorrhizal fungi play a significant role in water retention by extending a network of hyphae into the soil, effectively increasing the surface area available for water absorption, allowing plants to access water from a larger soil volume, and improving soil structure through aggregation, which helps the soil hold more water overall (Querejeta, 2017); this is particularly important in drought conditions where water availability is limited. This dramatically expands the absorptive areas of the plants, as they extend their root systems across a greater area. Fungal networks increase water retention in key ways (Querejeta, 2017). Firstly, the fungal hyphae are smaller than plant roots, and thus are able to reach into small soil pores that plants cannot access. This maximizes the surface area over which the plant/fungi can absorb water, increasing water uptake. Secondly, mycorrhizal fungi produce a sticky glycoprotein called glomalin, which causes soil particles to bind to each other, creating an aggregated soil clump that improves both water uptake and retention. This is of utmost importance in sandy soils that drain rapidly. These combine to allow plant-mycorrhizal symbiotic networks to increase their drought tolerance due to their enhanced ability to access water. All of this creates a system with increased hydraulic conductivity.

Mycorrhizal networks allow for enhanced organic matter accumulation, increasing plants' access to critical nutrients to support growth (Pappas, 2023). Taking a step back from the individual plant, these indirect mechanisms have the potential to increase plant health and overall ecosystem stability. This is where these networks are able to combat human induced climate change, including increased desertification, urbanization and the effects of ranching. Successful prairie restoration also relies on prioritizing native species, as these plants use significantly less water than non-native species (Cavaleri and Sack, 2010). Reintroducing native species, alongside fungal inoculations in restored southwest prairie environments will have an immense impact on the health and diversity of the area, helping to combat climate change and habitat loss. Protecting these vulnerable landscapes, at risk due to ranching and urban sprawl, and restoring native plants is critical for the health of the entire ecosystem.

**Figure 2.** Healthy Prairie Ecosystem
https://conps.org/project/plains-shortgrass-prairie/

This year's project is a continuation of last year, which modeled the role of mycorrhizal networks in signal spread in forests, deserts, and prairies. Last year's model found that mycorrhizal networks didn't have a significant impact in deserts or forests, with the low plant density of deserts preventing signal propagation and the high plant density of forests allowing for signal propagation irrespective of mycorrhizal networks. In prairies, however, higher fungal densities improved signal propagation between plants. This year, we expanded the variables in our model to more accurately mimic prairie ecology. Specifically, we differentiate between native and non-native grasses, examining the differences in water use and how mycorrhizal densities interact with each. We also added varying rain and storm patterns which are better aligned with recent real life data.

## Methods

Our prior project used NetLogo to model signal transduction in three ecologies using a cellular automaton model. The signal represented information exchange which was proven to have many benefits to plant health. This year we continue using Netlogo to expand our simulation, focusing on prairies and including the effects of native versus non-native grasses and the interaction of grass type with varying densities of mycorrhizal fungi. Instead of modeling the propagation of a signal, we are modeling the ways in which our variables predict the occurrence of healthy plants, creating a simplified ecological simulation specifically showcasing how fungi retain water and improve overall ecosystem health. In addition, we hoped to use our experimental results to quantify the effects of different inoculation densities of mycorrhizal fungi on water retention, as well as to verify the water needs of native versus non-native grasses. Unfortunately, our experiment did not yield the results we hoped for, as we experienced vandalism and a cold snap during which our school had no heat, and all of our grasses went dormant. As a result, we are relying on variable values from our research without being able to evaluate data from the physical experiment.

**Figure 3.** Dormant Grasses
Dr. Mueller 2025

## Variables

This year's model introduces additional variables relevant to prairie ecosystems. These include the ratio of native to non-native grasses, the density of fungal inoculations, and the probability of rain. Our model represents a square with 500 discrete patches, and patches may be separately available for plants, fungi, and water. Specifically, fungi and plants may share a patch, but each patch may not support more than one plant. The ratio of native to non-native grasses varies from zero to one hundred. When the plant ratio slider is set to zero, all plants are non-native; at 100, all plants would be native. Plant count is set from 120 to 250. Below 120 more closely mimics a desert ecosystem, where plants are very discrete and patchy. Above 250 more closely mimics a forest ecosystem, where plants are in close proximity and root systems overlap. To build on our more simplified model from last year, prairie plant density is set between those two extremes. With respect to our fungal networks, the density of fungal inoculations is set between zero and one hundred, creating up to 100 fungal areas. These areas are assigned randomly to one of the 500 discrete patches. Each fungal culture tries to attach to a plant, but may also exist without one. Fungal patches may affect up to 5 patches around them, increasing water retention by decreasing evaporation. They also have the ability to decrease the “stress” of nearby plants.

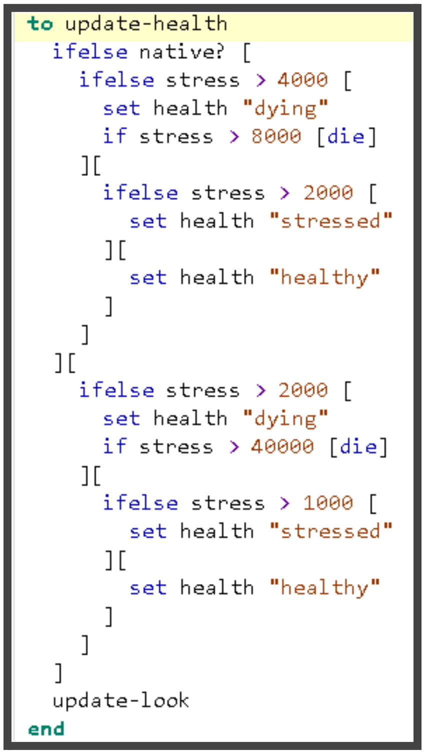
The probability of rain is determined by a slider set between 11% to 25%, which represents the probability of rain during the monsoon season (NWS Albuquerque, 2023) which determines the probability of rain at each 100 ticks. How often it rains is decided by the rain-probability slider every 50-5000 ticks. Rain also has multiple coverage and intensity conditions. Coverage determines how many patches are filled when it rains, between 1 and 5, as monsoonal rainfall is patchily distributed. Intensity determines the amount of water that fills each individual patch. Each patch can hold a maximum of 100 units of water when full. On average patches contain 20-30 units of water, as the model represents an environment where water is scarce. When it rains, the model randomly selects a number between 0-4, which choses one of 5 different storm types. 0 is the weakest, representing a light sprinkle with coverage ranging from 5-15 patches and intensity ranging from 0.1-0.3. Type 4 is the strongest representing a heavy storm with coverage ranging from 40-60 and intensity ranging from 0.4-0.9.

Our model is a two-layer system. The bottom layer represents water availability. The water level in the patch ranges from 0 to 100, with zero representing an empty patch and one hundred representing a completely full patch. When a patch is filled by rain, the level of water is determined by the intensity of the storm. Water depletes through both plant consumption and evaporation. During simulations 0.50 units of water diffuses into other patches every 10 ticks. Native plants require at least 15 units of water to be healthy; non-native plants require at least 30. Even if a patch does not hold the required amount of water to fill plant needs, the plant will still consume the available water in the patch. If a plant is not able to acquire enough water to be healthy, the patch will add a stress counter. The water requirements established from our background research drive both the water needs of native versus non-native plants, as well as the period of time each plant may exist as “stressed” without dying.

The stress counter for non-native plants is double that for native species, as they are not adapted to live in desert conditions. For all plants within the 5 patch area of fungi, stress levels decrease due to the absorptive function of their fungal neighbors, from 0-100 randomly, every 10 ticks. Native plants that are within 5 patches of a non-native plant will experience an increase in stress due to the increased water usage of that non-native neighbor. This increase will be from 0-100 randomly, assessed every 10 ticks. All plants have 4 different health states: healthy, stressed, dying, and dead. For native plants, their health state will transition from health to stress when they reach a stress count of 2000. When the stress counter reaches 4000, plants will move from stressed to dying. At a stress count above 8000, native plants die. Non-native plants experience these state transitions at values that are half those of native plants, due to not being acclimated to life in the arid environments.

While the model is running, plants may improve their health state by getting the required amount of water. For example, if a native plant's stress counter goes below 2000, it moves from stressed to healthy. Once a plant dies it is removed from the ecosystem forever. This doesn’t fully represent how these ecosystems work, because grasses are able to move to a state of dormancy like trees and can return when conditions are favorable. Additionally, in real ecosystems, plants are able to spread through both sexual reproduction, with seeds, and asexual reproduction, with runners. This variable was not included in our model in order to keep the number of variables manageable. but we did not have time to implement this even though we originally planned. In a real ecosystem, non-native plants can overwhelm native species and alter the local environment.

Below is a small sample of our NetLogo code, specifically addressing plant health state. Our full model is included in the appendix.



```
to update-health
  ifelse native? [
    ifelse stress > 4000 [
      set health "dying"
      if stress > 8000 [die]
    ][
      ifelse stress > 2000 [
        set health "stressed"
      ][
        set health "healthy"
      ]
    ]
  ][
    ifelse stress > 2000 [
      set health "dying"
      if stress > 40000 [die]
    ][
      ifelse stress > 1000 [
        set health "stressed"
      ][
        set health "healthy"
      ]
    ]
  ]
  update-look
end
```

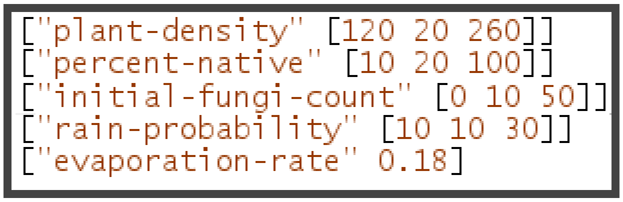
**Figure 4.** NetLogo code for plant health states.
Dorado, 2025

## Simulation Plan

Our original simulation plan included 27 experimental states (high, medium, low for each of our variables), with 100 simulations for each experimental condition. Our rain variable was originally set to occur at specific intervals, and we did not include rain intensity.  At our February judging, it was recommended that we randomize rain intervals and intensity to make it more accurately mimic real environments. It was also recommended we utilize BehaviorSpace through NetLogo to run our simulations and collect the data. This allowed us to run many more simulations than our original plan, without having to manually adjust our sliders.

BehaviorSpace is a tool integrated with NetLogo that allows you to run experiments with your model. While BehaviorSpace runs it varies the model's parameters and records the results of each run. This process is called "parameter sweeping". It also has the capacity to run multiple simulations in parallel. (NetLogo.com, 2025). We've succeeded in setting up BehaviorSpace and launching our simulations; we will have our full complement of simulations.

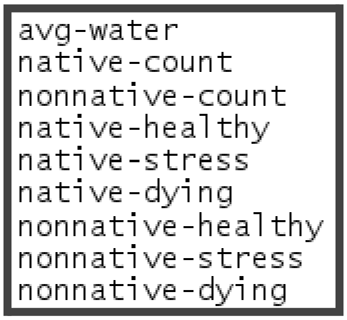
Since we were not able to run and analyze our full data set, the preliminary results are based on a smaller sample size. Our BehaviorSpace variables and repetition amount were altered for quicker turnaround on run times and easier data analysis. For example the increments for all variables were increased to 20, this means at each new run instead of altering the variables by 1 they are by 20. Our BehaviorSpace variables are below:



```
["plant-density" [120 20 260]]
["percent-native" [10 20 100]]
["initial-fungi-count" [0 10 50]]
["rain-probability" [10 10 30]]
["evaporation-rate" 0.18]
```

**Figure 5.** BehaviorSpace variables55
Dorado, 2025

Looking at the plant density variable as an example, the first number is the minimum value, the middle number represents the incremental increases, and the last number is the maximum value. This means it will use every value from 120 to 260 in increments of 20. While BehaviorSpace is running it measures reporter metrics. Our reporters are below:



```
avg-water
native-count
nonnative-count
native-healthy
native-stress
native-dying
nonnative-healthy
nonnative-stress
nonnative-dying
```

**Figure 6.** BehaviorSpace reporters
Dorado, 2025

BehaviorSpace can record metrics at every step/tick or at predetermined conditions.

(count plants = 0) or (ticks >= 16000)

We have set the model to stop and record data when all plants die or the simulation reaches 16000 ticks. After all runs are complete,  BehaviorSpace records all data and organizes it into a table which we analyzed for our preliminary results.

## Statistical Techniques

In order to understand the data we conducted a regression analysis. Regression analyses begin by identifying independent and dependent variables. The independent variables in our model include the ratio of native to non-native plants, density of fungal inoculations, evaporation rate, and available water, while the dependent variable is plant health. The main function of a regression analysis is to determine which variables have the most impact on a given outcome. This is accomplished by including the important predictors in the equation of the function of best fit, and assessing how much of the variance in the dependent variable is explained by this function of best fit. Another important aspect of regression analysis is an error term which is represented by a number. Each time we add another predictor variable to the model, the error term changes. When the error term is a large number there is not a strong correlation between the independent and dependent variables, while a smaller error term represents stronger correlation. The regression models were run in SPSS.

## Preliminary Results

We experienced some difficulties in setting up BehaviorSpace and getting our model to measure what we wanted to have it measure. Thus, we do not yet have our full sample size or our final analyses. However, our preliminary results are encouraging. With 1728 simulations, we ran regression models with healthy plants as our dependent variable and average water, fungal density, and evaporation rate as independent variables. We completed these separately for native plants and non-native plants. These regression models are all significant, with some slight differences in the effects of the independent variables.

### Native Plants

The model predicting native healthy plants is fairly robust, with an r-square value of 0.635. This shows that roughly 63.5% of the variance in native healthy plants is predicted by the ratio of native to non-native plants and the fungal density. For both of these, the effect is positive. Thus, having a higher proportion of native plants significantly predicts a greater outcome of native healthy plants. We propose that this is due to the increased water use of non-native plants. Denser fungal cultures yield a higher likelihood of native plants being healthy. We propose that this is due to the ways in which mycorrhizal fungal networks enhance water access and decrease water loss. These results are depicted in table 1 below.

**Table 1: Model Summary for Native Healthy Plants**

| R | R Square | Adjusted R square | Std. Error of the Estimate |
|---|---|---|---|
| .797 | .635 | .635 | 44.10109 |

**ANOVA**

| | Sum of Squares | df | Mean Square | F | Sig |
|---|---|---|---|---|---|
| Regression | 5842597.143 | 2 | 2921298.572 | 1502.025 | <.001 |
| Residual | 3354963.690 | 1725 | 1944.906 | | |
| Total | 9197560.833 | 1727 | | | |

### Coefficient

| | Unstandardized B | Coefficients Std. Error | Standardized Beta | t | Sig. |
|---|---|---|---|---|---|
| (Constant) | -44.785 | 2.359 | | -18.987 | <.001 |
| percent_native | 1.428 | .031 | .669 | 45.978 | <.001 |
| initial_fungi | 1.415 | .047 | .434 | 29.834 | <.001 |

## Non-Native Plants

The model predicting non-native healthy plants is also robust, with an r-square value of 0.710. This shows that roughly 71% of the variance in non-native healthy plants is predicted by fungal density, ratio of native to non-native plants, and the average water available. Denser fungal networks are associated with greater non-native plant health, as is the ratio of native to non-native plants. While average water was not significant for the health of native plants, it is a significant predictor of non-native plant health. These results are depicted in table 2 below.

### Table 2. Model Summary for Native Healthy Plants

| R | R Square | Adjusted R square | Std. Error of the Estimate |
|---|---|---|---|
| .843 | .710 | .709 | 16.61148 |

### ANOVA

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Regression | 1163773.316 | 3 | 387924.439 | 1405.823 | <.001 |
| Residual | 475722.572 | 1724 | 275.941 | | |
| Total | 1639495.888 | 1727 | | | |

## Coefficients

| | Unstandardized B | Coefficients Std. Error | Beta | t | Sig. |
|---|---|---|---|---|---|
| (Constant) | 43.207 | 1.810 | | 23.865 | <.001 |
| initial_fungi | .573 | .026 | .416 | 22.230 | <.001 |
| percent_native | -.591 | .015 | -.656 | -40.182 | <.001 |
| ave_water | -1.442 | .082 | -.372 | -17.595 | <.001 |

## Discussion

While we had lofty goals to run several thousand simulations before the final report was due, we were unable to meet this deadline. We encountered challenges within our code which required more time and assistance to resolve. In addition, we had to familiarize ourselves with BehaviorSpace as it was our first time using the software. We had numerous resources to help us throughout the process which helped us maintain steady progress, and we are eager to continue running our simulations and having a more complete data set and analyses at the Expo.

Our model also went through several iterations between the February judging and this Final Report. Before our Interim Report, we had hoped we would be able to use the results from our experiment to inform the variables in our model. As we approached the February judging, it became evident that the experiment would not produce the results we needed, and we pivoted to base our code on variables from our background research. At the February judging, our model consisted of the following variables: plant density, ratio native to non-native, fungi count, evaporation rate, and water refill quantity. This model was much less complex then our current model. Plants needed specific fractions of water (native needed ⅓ of a full patch) and if they didn't get this full amount of water within a predetermined time they would die. Non-native and native plants functioned in the same way, but non-native plants needed more water than natives (½ of a full patch). Fungi only impacted water evaporation based on how many fungi there were in the model total. Rain was set to occur at predetermined time increments and only the % of patches that were filled at this time could vary. When a patch was filled it was filled to full, or 1 unit, every time.

At the February judging, it was suggested that the rain should be more randomized and multiple states of plant health should be included. We have subsequently incorporated the Judges ' suggestions and expanded our model to accommodate these. Our revised model now includes: plant density, ratio of native to non-native, fungi count, evaporation rate, and rain probability. Patches are able to hold more water, up to 100 units, and plants are able to take in any amount of water from their patch. We've also included stress counters, which are activated in response to water available versus water needs. Rain was changed to a probabilistic likelihood, and is now based on a rain probability slider which determines the chance of rain every 150-2000 ticks. Instead of % of patches filled being based on the slider, and all patches filled to full, coverage and intensity are randomized each rain cycle. The ratio of native to non-native plants also plays a more significant role in ecosystem health as they increase the stress of nearby native plants. Fungi now only reduce the evaporation rate of patches around them but now additionally decrease the stress of plants within their area. All of these factors fed into and affected new plant health states: healthy, stressed, dying, and dead. This not only made our model more complex but assisted our data in becoming more accurate to real life conditions of  the desert southwest.

Additionally, as we started to compile our preliminary results, we tweaked our model slightly in order to more accurately reflect real ecological characteristics as well as to automate the process of data collection and allow for more continuous contrasts in our predictor variables, rather than static categories across which we would compare. This lends itself more to regression analysis than analysis of variance (ANOVA), as our predictors represent continuous variables.

When looking at the preliminary results, we are encouraged by the differences in the models between native and non-native species. Our background research highlights the difference in water demands between native and non-native species. Our model appears to support this fact, and water availability is not a significant predictor of plant health in native species. For native species, the ratio of native to non-native plants is a significant predictor of plant health. We propose this is due to the fact that non-native plants have such significant water usage/requirements that having too many of these present significantly affects the health of native plants in proximity. The same variable is an important predictor in non-native plant health as well, likely due to the same action - the increased water usage/demands of non-native plants.

Fungal density is also an important predictor of plant health for both native and non-native plants. Ultimately, this supports the entire hypothesis we used to drive our multi-year project. While we were not able to verify this through a physical experiment, we are incredibly encouraged that our modeling supports this. Arbuscular mycorrhizal fungi are easily purchased at nurseries and online at a fairly low cost. These come in a dehydrated, stable form, and can readily be added to soil as you seed or plant. These should be added to any sort of planting undertaken in arid areas. This positive impact of supplementing with arbuscular mycorrhizal fungi has been supported by one restoration project, and is worth investigating on both small scales and large scales. This action has profound implications for how restoration efforts should be undertaken.

Lastly, the availability of water is an important predictor of the health of non-native plants. This is not surprising, given the increased water demands of non-native species. While our model found that this variable did not impact the plant health of native species, we believe this is a little misleading. Having available water absolutely affects whether native species succeed or not. But native species are uniquely adapted to our arid environments, and are better able to flourish with lower water availability. In fact, the situations where water availability would have a larger effect on plant health are likely to be those where native species are competing with non-native species to access limited water resources. In our model, this is captured by the ratio of native to non-native species, and water availability does not have a significant effect after that ratio is accounted for. For non-native species, while the ratio influences plant health, the water needs of non-native species also lead to an additional effect after that ratio is accounted for.

## Conclusion

This project examined the role of mycorrhizal fungi in arid prairie environments. We expanded our project from the previous year, which explored how mycorrhizal fungal networks aided signal propagation in deserts, forests, and prairies. We found that mycorrhizal fungal networks play an especially important role in prairie ecosystems. Our current project focused solely on these arid prairie environments, modeling how mycorrhizal fungal density, plant density, the ratio of native to non-native grasses, evaporation rate, and water availability affect overall plant health. We utilized NetLogo to build our model, working with BehaviorSpace as an add-on, and analyzed our preliminary results using SPSS. Those preliminary results support the importance of mycorrhizal fungal densities, coupled with native plants, in promoting overall plant health.

In the future, we plan to run more simulations and analyze the results from a larger sample size. This will give us the opportunity to have a more comprehensive view of the data. Once all of our simulations are complete, we will conduct a more extensive regression analysis, with a much larger sample size. This will allow us to have greater statistical power and confidence in our conclusions. Additionally, we would love to disseminate this knowledge to the wider world as a whole, as these recommendations have the benefit of having an overall positive effect on the success of restoration efforts and mitigating climate change and increasing aridity.

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**Appendix: Compete Code**

```
breed [plants plant]
breed [fungi fungus]

plants-own [
  native?
  dry
  health
]

fungi-own []

patches-own [
  water
]

globals [
  avg-water
  rain-count
  native-count
  nonnative-count
  native-healthy
  native-stress
  native-dying
  nonnative-healthy
  nonnative-stress
  nonnative-dying
  fungi-count
  last-rain-patches
  last-storm
  next-storm
]

to setup
  clear-all
  reset-ticks

  ask patches [
    set water random-normal 50 20
    update-color
  ]

  create-plants (plant-density * 1) [
    let spot one-of patches with [not any?
plants-here]

    ifelse spot != nobody [
      move-to spot
      set native? random 100 < percent-native
      set health "healthy"
      set dry 0
      set color 53
      set size 1
      update-look
    ] [
      die
    ]
  ]

  create-fungi initial-fungi-count [
    move-to one-of patches
    set color 35
    set size 1
    set shape "dot"
  ]

  set rain-count 0
  set last-rain-patches no-patches
  set last-storm ""
  set next-storm ticks + random-normal 100
50
end

to go
  if any? last-rain-patches and ticks mod 10
= 0 [
    ask last-rain-patches [update-color]
    set last-rain-patches no-patches
    set last-storm ""
  ]

  if ticks >= next-storm [
    set rain-count rain-count +
(rain-probability + 50)

     if rain-count > 0 [
```

```
      let storm-type random 5
      let intensity 0
      let coverage 0

      (ifelse
        storm-type = 0 [
          set intensity 0.1 + random-float 0.2
          set coverage 5 + random 10
        ]
        storm-type = 1 [
          set intensity 0.15 + random-float 0.25
          set coverage 10 + random 15
        ]
        storm-type = 2 [
          set intensity 0.2 + random-float 0.3
          set coverage 20 + random 30
        ]
        storm-type = 3 [
          set intensity 0.3 + random-float 0.4
          set coverage 30 + random 20
        ]
        storm-type = 4 [
          set intensity 0.4 + random-float 0.5
          set coverage 40 + random 10
        ]
      )

      set coverage min list 100 coverage
      set intensity min list 1 intensity

      let patch-count round (count patches *
coverage / 100)
      let rain-patches no-patches

      set rain-patches n-of (
        min list patch-count count patches
      ) patches

      ask rain-patches [
        let fill random-normal (intensity * 20)
(intensity * 15)
        set water water + max list 1 fill
        update-color
      ]
```

```
      set last-rain-patches rain-patches
      set rain-count 0
      set next-storm ticks + random-normal
37.5 100
    ]
  ]

  if ticks mod 10 = 0 [diffuse water 0.50]

  if ticks mod 10 = 0 [
    ask plants with [not native?] [
      let nearby-natives plants with [
        native? and distance myself <= 4
      ]
      ask nearby-natives [
        if random 100 < 50 [
          set dry dry + random 100
          update-health
        ]
      ]
    ]

    ask plants [
    let nearby-fungi fungi with [distance
myself <= 4]
    ask nearby-fungi [
        let transfer random 100
        ask myself [
          set dry dry - max list 100 (dry -
transfer)
          update-health
        ]
      ]
    ]
  ]


    ask plants [
      let water-needed 30

      let available [water] of patch-here

      ifelse available > 0 [
```

```
        let ratio available / water-needed
        let take min list available water-needed

        ask patch-here [
          set water max list 0 (water - take)
          update-color
        ]

        ifelse ratio >= 1 [
          set dry 0
          set health "healthy"
        ] [
          set dry max list 0 (dry + (100 * (1 - ratio)))
          update-health
        ]
        update-look
      ] [
        ifelse native? [
          set dry dry + 1
        ] [
          set dry dry + 10
        ]
        update-health
      ]
    ]


  if ticks mod 10 = 0 [
    ask patches [
      let evap-rate evaporation-rate * 2.5
      set water water * (1 - evap-rate)
      update-color
    ]
  ]

  if ticks mod 10 = 0 [
    set native-count count plants with [native?]
    set nonnative-count count plants with [not native?]
    set native-healthy count plants with [native? and health = "healthy"]
    set native-stress count plants with [native? and health = "stressed"]
    set native-dying count plants with [native? and health = "dying"]
    set nonnative-healthy count plants with [not native? and health = "healthy"]
    set nonnative-stress count plants with [not native? and health = "stressed"]
    set nonnative-dying count plants with [not native? and health = "dying"]
    set fungi-count count fungi
    set avg-water mean [water] of patches
  ]

  tick
end

to update-health
  if native? [
    if dry > 40000 [set health "dying" update-look]
    if dry > 10000 and dry <= 40000 [set health "stressed" update-look]
    if dry <= 10000 [set health "healthy" update-look]
    if dry > 80000 [die]
  ]

  if not native? [
    if dry > 2000 [set health "dying" update-look]
    if dry > 1000 and dry <= 200000 [set health "stressed" update-look]
    if dry <= 1000 [set health "healthy" update-look]
    if dry > 40000 [die]
  ]
end

to update-look
  if native? [
    ifelse health = "healthy" [
      set color 53
    ] [
```

```
      ifelse health = "stressed" [
        set color 43
      ] [
        set color 33
      ]
    ]
  ]

  if not native? [
    ifelse health = "healthy" [
      set color 13
    ] [
      ifelse health = "stressed" [
        set color 23
      ] [
        set color 133
      ]
    ]
  ]
end

to update-color
  let water-ratio min list 1 (water / 100)
  set pcolor rgb
    (255 - (255 * water-ratio))
    (255 - (255 * water-ratio))
    255
end
```