The Wood-Wide Web's Impact on Plant Health in Arid Areas

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Mycorrhizal networks, or the "Wood-Wide Web," play a vital role in facilitating information exchange among plants. These networks allow plants to share crucial information about things such as water availability, pathogen prevalence, localized environmental dangers, and more. In arid regions, like New Mexico, aridity significantly affects mycorrhizal networks, affecting the efficiency of information transfer. Our project focuses on how these networks impact plant health in arid places, especially in New Mexico.

Introduction

In forests, there is a significant overlap of root systems between plants and fungi. When trees and other herbaceous growth do not have root systems that overlap, mycorrhizal networks, with their mycelia, may allow trees to send warning signals to inform each other of threats. (Holewinski,accessed 2024). This process, known as "underground networking," is crucial for the survival of various plant species. In the wild, mycelium can be observed as threadlike strands called hyphae. Hyphae are the “roots” of fungi. Just like a plant’s roots, they break down organic matter into smaller parts to feed fungi and other organisms. Mycorrhizal networks come in a range of sizes, with some types growing to enormous proportions, (Johnston and Brewer, 2023) such as the largest organism on Earth, a single honey mushroom with a mycelial spread of 4 square miles (Hogan, 2022)! These networks are often mediated by one or a few “mother trees”, and trees have been shown to recognize their relatives and preferentially favor them when transferring carbon and nutrients. In exchange, the mycorrhizal networks keep about 30% of the sugar the plants feed into the network, using that as fuel, but transfer phosphorus and other mineral nutrients back into the plants (Holewinski,accessed 2024).

In more arid environments, wild spaces are more likely to be prairies, and these are among the most threatened habitats globally. New Mexico has historically hosted significant areas of shortgrass prairie in the east and desert grasslands in the south, supporting hundreds of local ecosystems.These prairies are threatened by residential sprawl, energy development, agriculture, and climate change (Nature Conservancy, 2018). When these prairie ecosystems are degraded by things like ranching and urban sprawl, native species suffer, and these habitats experience increasing ‘desertification.’ This opens up these prairie ecosystems to shrub encroachment, and current estimates demonstrate that over 35,200 km2, or 8.7 million acres, are affected (US Department of the Interior, accessed 2024). This is also associated with increases in spread and density of invasive species (New Mexico Noxious Weeds, accessed 2024).

Not only are plants of arid areas uniquely adapted to environmental conditions; fungi are as well. Arbuscular mycorrhizal fungi are associated with 80% or more of plants in terrestrial ecosystems, arid environments included, and are uniquely positioned to help desert plants tolerate stress. They do this by producing hyphae that are able to access small soil pores. This allows these mycorrhizal networks to increase their ability to take up water from the ground. In experimental drought conditions, water-limited plants even allocate more resources and biomass to these mycorrhizal fungi (Vasar et al., 2021). However, extremely arid and nutrient poor areas develop non-mycorrhizal fungi in greater densities, to the overall detriment of native ecosystems.

Recent experiments addressing restoration efforts have highlighted the need for native mycorrhizal fungi inoculations to more successfully re-establish native plants in prairie ecosystems. Specifically, Koizoil et al. (2018) have shown that the greatest success of grassland restorations occur with the greatest density of late successional arbuscular mycorrhizal fungi. These restoration efforts are of critical importance to the health native ecosystems because restoring native plants has extreme benefits like aiding in soil restoration and water retention. Additionally, many native species have evolved to have specialized relationships with native plants and pollinators, and one or more species depend on each other for survival (symbiosis). Native plants benefit their ecosystems through their adaptations to their local environments, and don’t demand excess water and nutrients. Furthermore, the benefits from restoring native plants impact all life ecosystems, from plants and insects through larger bodied animals like birds, bears and even humans. This is because plants are the cornerstone of all food-webs; with an invasive or otherwise nonnative plant population the negative effects cascade throughout the web.

While prairies may harbor significant fungal populations, protection efforts are crucial to safeguard these essential yet vulnerable landscapes. In dry areas, these fungal networks help plants share information. We want to investigate how arid conditions affect these networks and what it means for plant communication. We also hope to highlight the importance of re-establishing native prairies with healthy populations of both native plant species and mycorrhizal fungal species.

Methods/Model

We aim to model how efficiently plants communicate in each environment. Specifically, we are interested in how restoring natural prairies can impact plant growth, water conservation, and climate change mitigation. We initially thought we would develop a

neural network model, but instead built a cellular automaton model, relying on NetLogo's capabilities to simulate complex interactions in ecosystems. The code is heavily based on preexisting code from Gitjub and public Netlogo models.
Our model simulates how signals travel through environments with different plant densities and mycorrhizal fungi densities. These include forests (90% plant density), prairies (75%plant density), and deserts (50% plant density). Within each habitat type, we further adjust mycorrhizal fungal densities in each, with 90%, 75%, and 50%. Reducing both plant density and fungal density below 50% results in a model in which signals do not spread at all. The specific ‘signals’ are not designated, but could include things like pathogen prevalence, water scarcity, nitrogen deficiency, or other external risks/exposures. Our models only represent stereotypical ecosystem characteristics, rather than a specific local environment.

The code is a patch system: green patches are plants and blue patches are mycorrhizal networks. A signal, represented as a red patch, moves across the screen when it comes into contact with neighboring patches. Plant patches without associated mycorrhizal patches have a small, but nonzero chance of transmitting the signal. Those with many mycorrhizal patches have reliable signal spread, transmitting the signal 100% of the time.

Results

Our first attempt at simulating the transmission of signals through the ecosystems we chose to model produced data that did not support our hypothesis. This model treated mycorrhizal fungi as completely independent from plants and including various ‘strengths’ of mycorrhizal networks. This model demonstrated a decrease in signal transmission correlated with higher mycorrhizal destinies, rather than an increase. This model also showed quite a bit of ‘noise’ that did not always allow the model to run to completion. As we reflected on the data from these simulations, we decided that the data wasn’t accurate and this most likely was due to problems in how we set up our model. We modified how we populated our mycorrhizal patches, eliminating differences in the strength of mycorrhizal patches and associating mycorrhizal patches with plant patches instead of randomly distributed throughout the plot. Figure 1 shows this decline in signal transmission in prairies from our first (and failed) model.

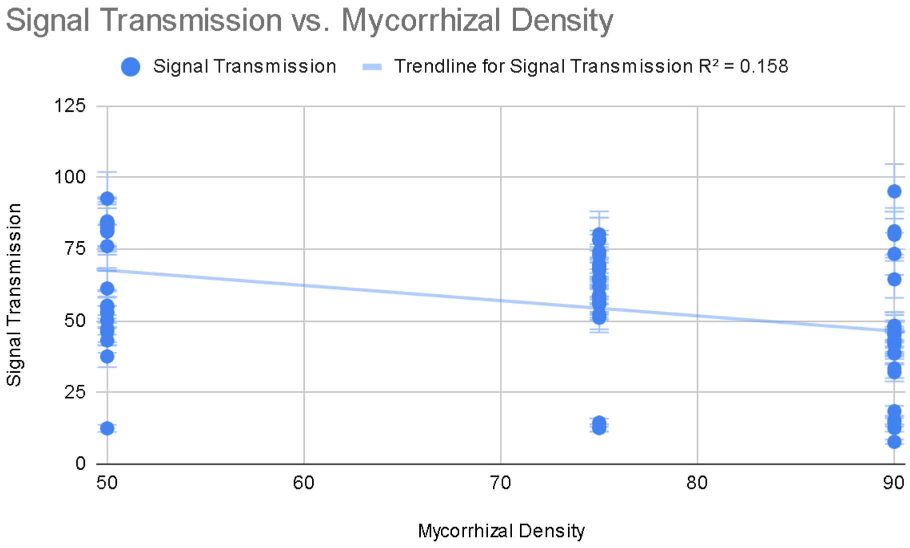


Figure 1. This figure shows a decline in signal transmission in prairie ecosystems associated with increasing mycorrhizal densities. This is from our first model.

Our second model is more ecologically accurate by associating mycorrhizal patches with plant patches. The results from this model are depicted in Figures 2, 3, and 4.

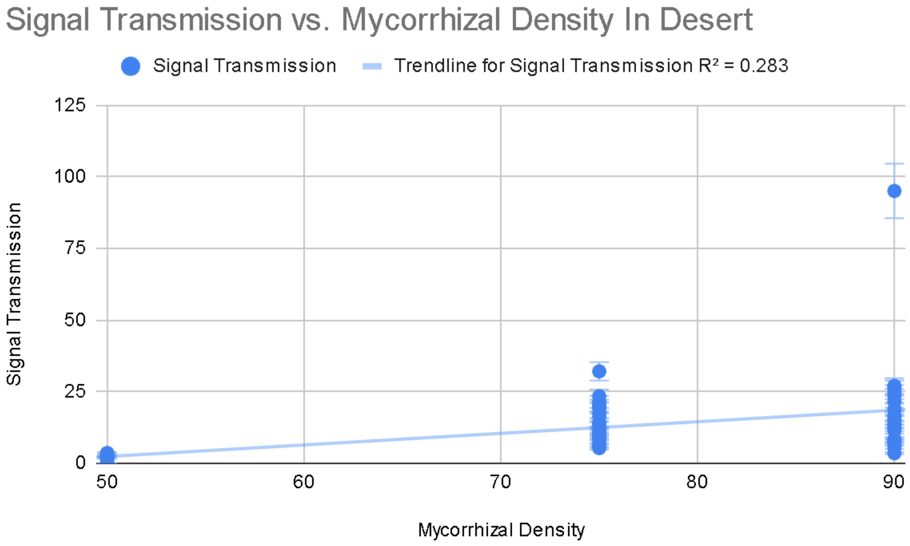


Figure 2. This figure shows the effect of mycorrhizal density on the spread of signals in desert environments. Plants in desert environments are situated very far from one another, minimizing the likelihood that mycorrhizal fungi will be able to network and spread signals.

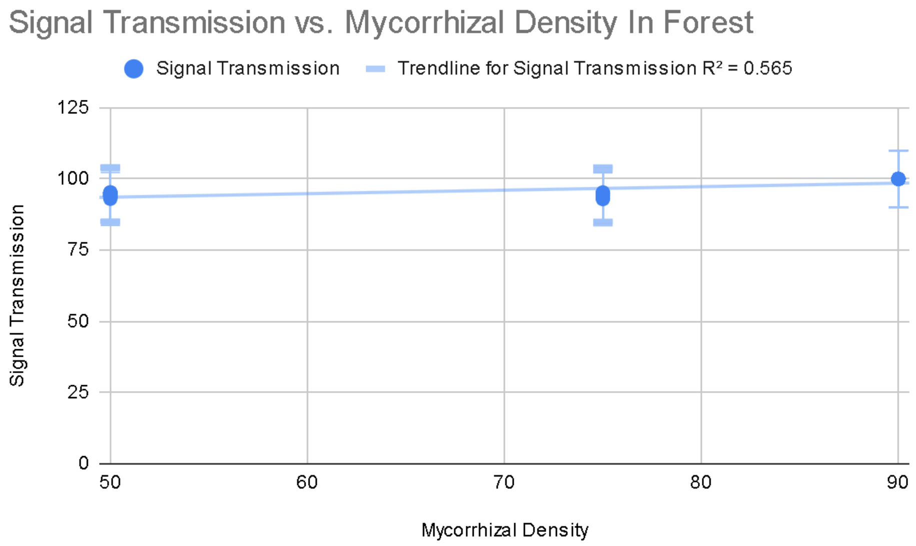


Figure 3. This figure shows the effect of mycorrhizal density on the spread of signals in forest environments. Plants in forest environments are situated very close to one another, minimizing the effect of mycorrhizal fungi on signal transmission due to more complex and integrated root systems.

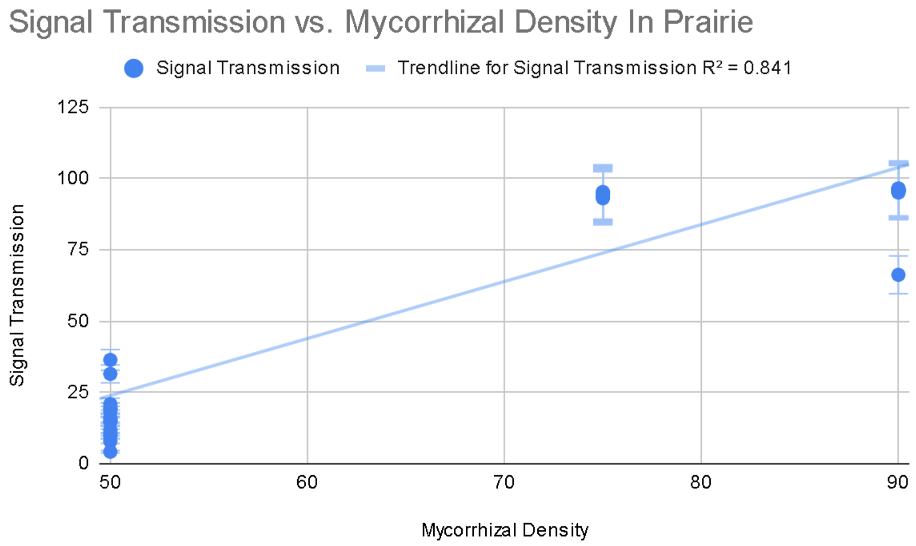
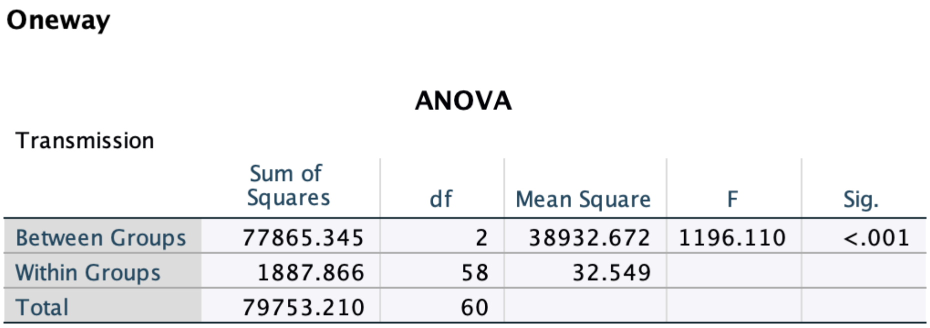


Figure 4. This figure shows the effect of mycorrhizal density on the spread of signals in prairie environments. Plants in prairie environments vary in their distance from one another. They are often not close enough for root systems to overlap, but close enough for mycorrhizal networks to have a significant positive effect on signal transmission.

As you can see in the above figures, plant density has a very strong influence on the effectiveness of mycorrhizal fungi in propagating signal transmission. In deserts, the plant density is very low and plants are very far apart, making the mycorrhizal fungi ineffective because, even with the addition of fungi, the signal can't spread because of the distance between plants. In forest ecosystems, the plant density is high, and root structures overlap considerably, rendering the mycorrhizal fungi less impactful on the spread of signals. In prairies, the plants are far enough that their roots don't overlap but the mycorrhizal fungi are able to link these root systems between plants.

While graphing our data provided a good overall view of the nature of the relationship between mycorrhizal fungi and plants, our model was also able to provide more details. Specifically, statistical analyses give us some insight into how strong these effects are. With our data we ran two different types of analyses. The first was an ANOVA, or Analysis of Variance. An ANOVA allows us to compare across categories.The categories we were interested were our densities of mycorrhizal fungi. Specifically, we compared across low (50%), medium (75%), and high (90%). As you can see from the table below, the ANOVA analysis indicates a significant difference between populations, with a p-value of less than 0.001. While this supports our hypothesis, post-hoc (after the fact) comparisons are necessary to determine where those differences lie.



Oneway

ANOVA

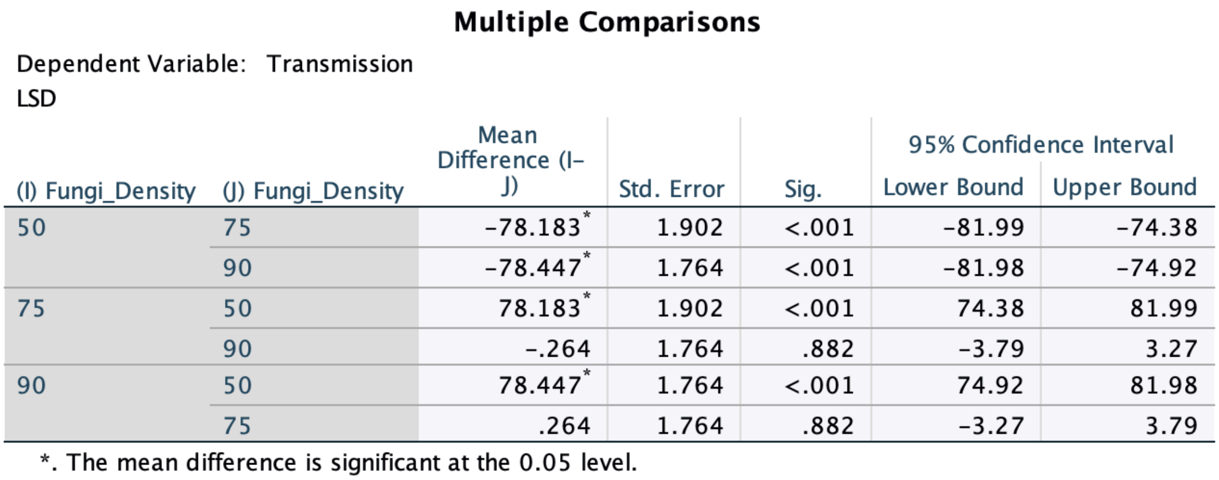
Transmission

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	77865.345	2	38932.672	1196.110	<.001
Within Groups	1887.866	58	32.549		
Total	79753.210	60			

Figure 5. This table shows the overall model results from our ANOVA (Analysis of Variance). This indicates that there are significant differences between categories (low, medium, high) of mycorrhizal fungi density. Figure 6 below shots the results of the post-hoc comparisons.

The post-hoc analyses demonstrate the variance between the different groups of data. As you can see, there are significant differences between low and medium densities and low and high densities. When we compare medium and high densities, the differences are not significant. This may reflect a threshold beyond which adding additional mycorrhizal fungi makes little impact. This threshold appears to be around 75% mycorrhizal density, adding more mycorrhizal fungi does not make a significant difference.

Post Hoc Tests



Multiple Comparisons

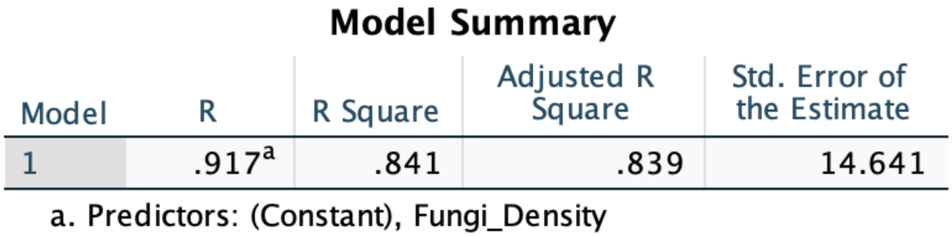
Dependent Variable: Transmission
LSD

(I) Fungi_Density	(J) Fungi_Density	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
50	75	−78.183*	1.902	<.001	−81.99	−74.38
	90	−78.447*	1.764	<.001	−81.98	−74.92
75	50	78.183*	1.902	<.001	74.38	81.99
	90	−.264	1.764	.882	−3.79	3.27
90	50	78.447*	1.764	<.001	74.92	81.98
	75	.264	1.764	.882	−3.27	3.79

*. The mean difference is significant at the 0.05 level.

Figure 6. This table shows the results of the post-hoc tests of our ANOVA. There are significant differences between low mycorrhizal density and both medium and high density. Specifically, simulations with low mycorrhizal densities are much less likely to transmit the signal effectively than those with medium and high densities.

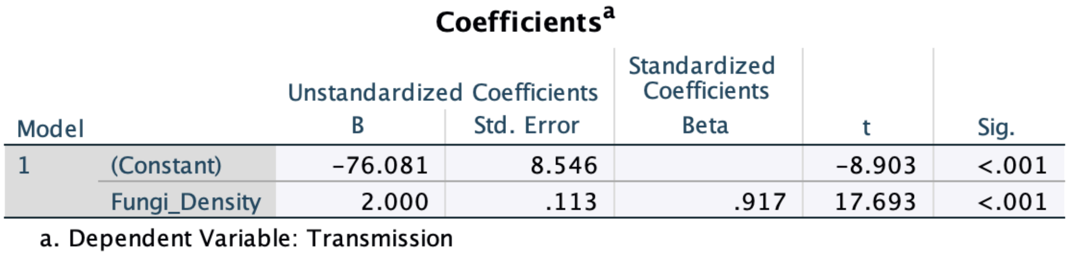
While the ANOVA allows us to identify differences between these levels of mycorrhizal densities, it does not allow us to determine whether mycorrhizal density *predicts* signal transmission. In order to assess this relationship, we ran a linear regression model with signal transmission as the dependent variable and mycorrhizal density as the independent variable. The results are summarized below.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.917[a]	.841	.839	14.641

a. Predictors: (Constant), Fungi_Density



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	−76.081	8.546		−8.903	<.001
	Fungi_Density	2.000	.113	.917	17.693	<.001

a. Dependent Variable: Transmission

Figure 6. These tables show the results of our regression model predicting signal transmission. This regression model indicates that mycorrhizal density is a significant predictor of signal transmission,

predicting 84.1% of the variability in our prairie data. Increasing mycorrhizal density is associated with increases in signal transmission.

As you can see above, it shows the results of our regression model at predicting the signal transmission. It indicates that the mycorrhizal density can be a significant influence in predicting the signal transmission.

Conclusion:

Our project has illuminated how plants and fungi are intimately intertwined. We modeled signal transmission across three ecosystems - forest, prairie, and desert. Simulations with forest-specific plant densities (set to 90%) indicate that while mycorrhizal fungi may play some role in plant health as measured through signal transmission, these effects are limited. This is due in part to the fact that plant root systems experience significant overlap, fostering strong connections. In contrast, deserts had very weak signal transmission between plants due to the distance between more isolated plants. Additionally, there is more competition for water in arid environments, making each plant's hydration more of a priority than helping its neighbors.

While validating our previous assumptions about forest and desert ecosystems, our prairie simulations proved significant. Mycorrhizal connections are essential to prairie health. While prairie plants are patchy in distribution, with root systems that spread deep with less root overlap, it is often not enough to effectively transmit the signal. However, prairie plants are close enough to be able to use mycorrhizal fungi to link the gap between plants. Furthermore, larger densities of mycorrhizal fungi allow for greater signal transmission.

New Mexico used to be characterized by short grass prairies, desert grasslands and basin shrubland. With agricultural intensification, increasing population numbers, and climate change, many arid grasslands end up becoming desert. This is definitely the case in New Mexico. Our model is intended to indicate potential solutions to this increasing desertification, solutions that include the reestablishment of prairies. These restoration efforts will be aided by considering not only the plant species to reintroduce, but also including appropriate mycorrhizal fungi, both in species types and in density. These efforts would have the greatest impact by including native species. Modeling the differences between native and non-native species was beyond the scope of this model, but should be considered in the future.

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