Mycorrhizae Inspired Building Networks: An Overview of Current Literature and Future Implications

Kaitlin Girard

Departments of Agriculture and Architecture, Alfred State College

AGRI 4900: Architecture of Natural Systems

Advised by Professor Jessica Hutchison

December 15, 2022

Abstract

Mycorrhizal networks facilitate interplant communication between trees, giving them the ability to ‘talk’ to one another, sending resources, nutrients, and allelochemicals via hyphae connections. Due to this high level of interconnectivity within forests, tree-partnering mycorrhizae play a major role in the circular economy of the ecosystem, supporting cyclic growth and death of each living entity. Industrial symbiosis within industrial ecosystems mimics this biological circular economy, and energy microgrids have modeled blockchain transactional behavior on the forest communication that is facilitated by mediating mycorrhizae.

Keywords: autonomous energy system, biomimetic design, industrial ecosystem, industrial symbiosis, microgrid, mycorrho-grid, mycelium architecture

Mycorrhizae Inspired Building Networks: An Overview of Current Literature and Future Implications

Introduction: Mycorrhizal Networks and *tree-talk*

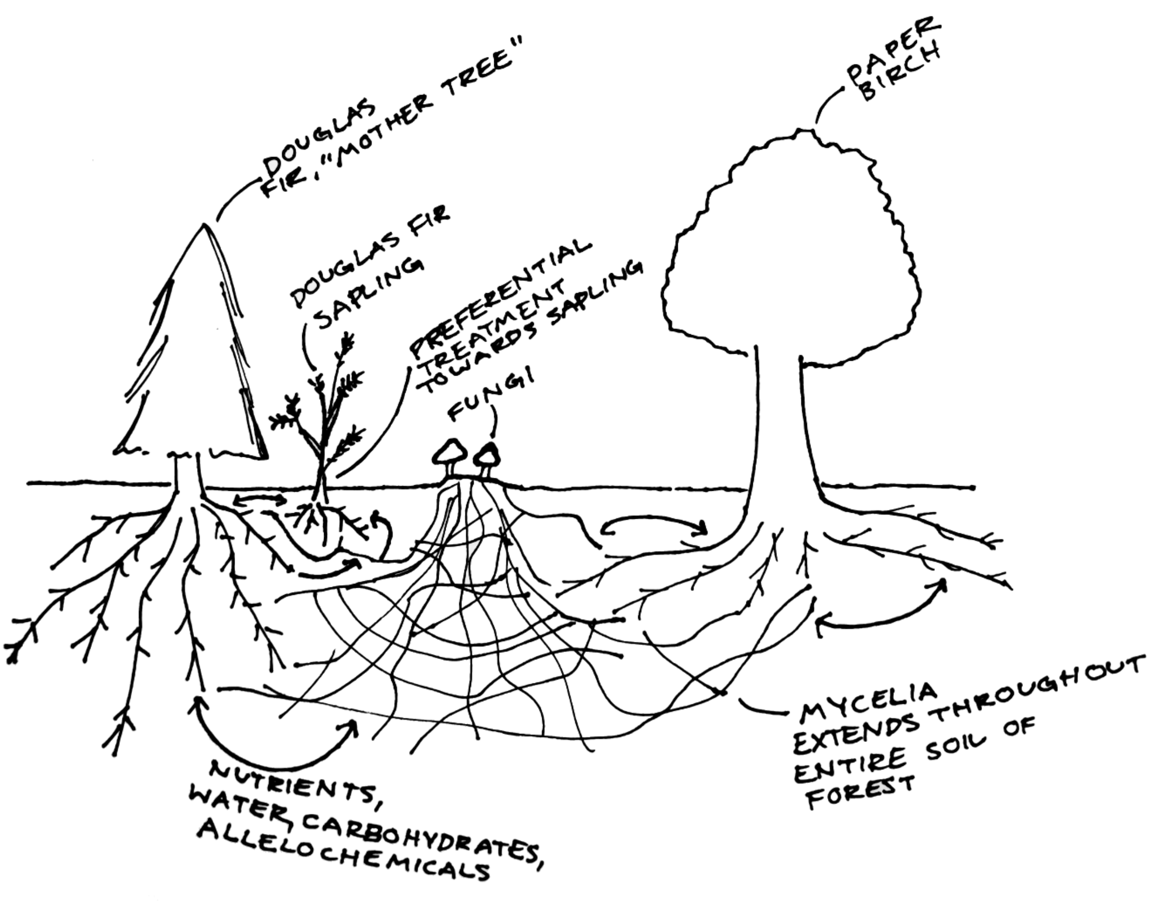
Trees have the ability to 'talk' to one another, sending resources, nutrients, and allelochemicals that signal behavioral responses to defend against a potential threat. This interplant communication helps not only to regulate the health of each individual tree, but also the collective health of the forest (Simard et al., 1997). One may ask, *how does this 'tree-talk' work?* While trees can send signals via volatile molecules in the air, another answer lies unsuspecting, beneath our feet—miles of microscopic mycorrhizal networks act as a middle manager to create a vastly interconnected social network of trees that can more readily adapt to environmental threats and changes (Simard et al., 1997). Among some of the species that have been studied for this are Douglas Fir trees (Pseudotsuga menziesii var. glauca) with Rhizopogon vesiculosus and Rhizopogon vinicolor fungi (Beiler et al., 2010), and communication between Paper Birch (Betula papyrifera) and Douglas Fir trees as compared to collocated Western Redcedar trees (Thuja plicata) that were not linked into a mycorrhizal network (Simard et al., 1997).

But why would these mycorrhizae want to help the trees? While the mechanism is complex, the answer is simple—the trees are not the only party benefitting from this relationship, the mycorrhizal fungi are too. Fungi cannot photosynthesize like trees can; these fruiting bodies of mycelium are heterotrophic, and contain no chlorophyll to convert sunlight into usable food energy. In order to obtain the carbohydrates they need to survive, they must absorb them from other organisms, such as trees (Smith & Read, 2010).

In exchange for excess carbohydrates received from forest residents (trees), the mycorrhizal network helps to supply its providers with essential nutrients such as isotopic carbon, nitrogen, phosphorous, and water, as well as the allelochemical signals sent by other trees. The hyphae also help increase the surface area that tree roots are able to absorb these nutrients and water from, therefore creating a symbiotic relationship (Francis & Read, 1984). Broken down into two types of symbiotic mycorrhizal relationships, ectomycorrhizal mycelium positions itself around the tree root cells, while endomycorrhizal mycelium penetrates into the cortical cells of the tree root. Both methods of this relationship still facilitate transactional exchanges between the tree and the fungi, and both still follow the same principal of beneficial mutual survival.

Figure 1

Diagram depicting how mycorrhizal tree-talk is facilitated



It is in the best interest of the mycorrhizal network to support and defend its hosts, as any loss of a host (tree), results in one less source of energy, and a potential decrease in biodiversity within its portfolio of mutualistic organisms. This explains why nutrients and water are not the only resources mycelium will barter with directly with trees; they also help facilitate inter-plant bartering and communication (Simard et al., 1997). An example of this is the kinship model, in which mother trees are able to send essential nutrients to their saplings that will help them grow, via the mycorrhizal mediator. While the mycorrhizae does not immediately benefit from the interaction, it has evolved to facilitate these interactions with the purpose of a prolonged increase in resilience, enhancing its chance for longevity. By adding more trees (such as the saplings) to its network, it will be better prepared to lose some of its forest resources. Likewise, the fungi will also facilitate dying trees sending out mass amounts of phosphorus to adjacent trees within the ecosystem, as a last attempt to share energy that it can no longer benefit from, acting in the best interest of the forest overall (Eason et al., 1991).

It is this mutual altruistic, yet self-preserving nature of the mycorrhizal relationships that forests have with fungi, that can help inform our building networks. The way that building systems operate today is highly compartmentalized and individualized, and even when buildings do tap into shared resources, such as the power grid, these utility systems are centralized around several separate entities, rather than a connected network that acts in the best interest of the overall health of the system. The way that mycorrhizal facilitated *tree-talk* works is essentially the biological equivalent of a circular economy. Trees grow, and live their lives being supported by mycelia in the aforementioned mutually beneficial exchange of resources; when they die, they send nutrients to help other trees, then eventually become decomposed by the same hyphae that has supported them their whole lives; leftover nutrients return to the same soil where a new sapling can grow in its spot and join the mycorrhizal network itself. This cycle continues, endlessly so long as a forest lives. The goal of this review is to illuminate the current ways in which our building systems have begun to model themselves after this process, and identify future projections of how this biological knowledge can be further applied to the field.

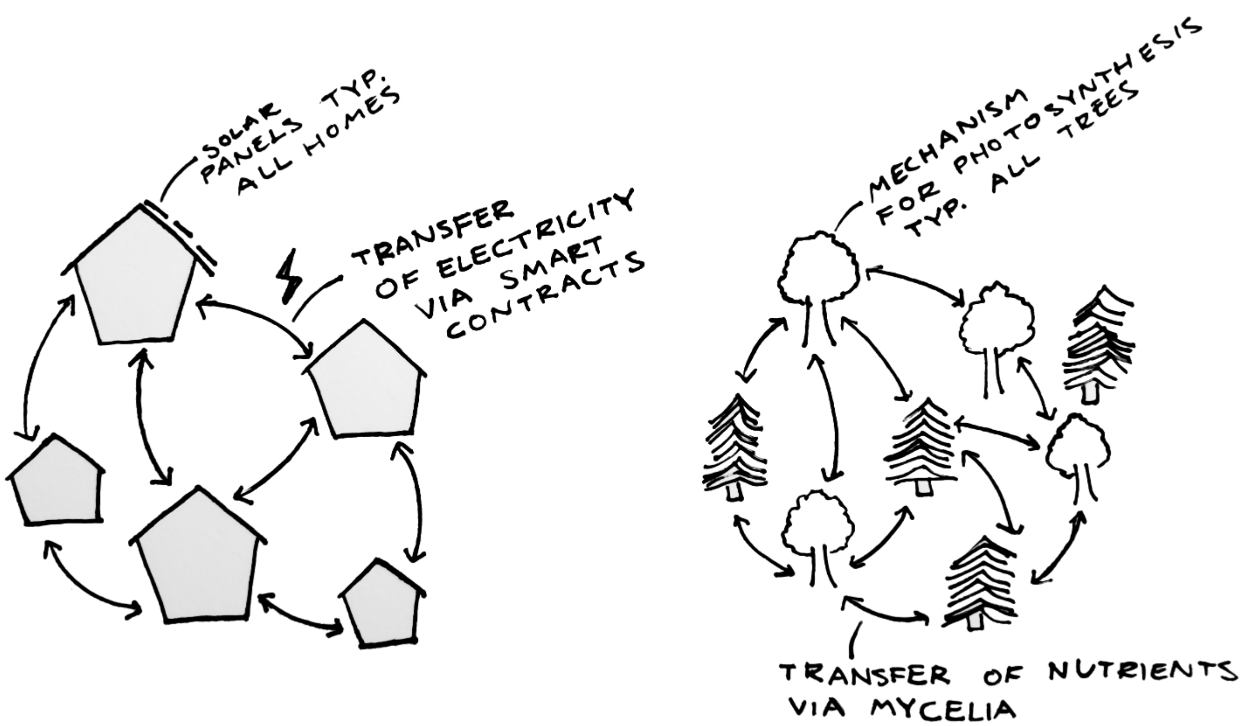
Critical Analysis Focus Area 1: *The Microgrid*

The United States currently operates on a centralized power grid system. While not truly a national grid, the grid is divided into three centralized regional grids, the Eastern, Western, and Texas interconnections, that act as self-contained zones for electricity production, transmission, and distribution. The power that is generated (often by fossil fuels) is sent across long distances anywhere within the plant's identified regional grid via high-voltage transmission lines to localized substations that convert it into a lower voltage electricity to be sent consumers. Because these grids span such large distances, and are centralized monopolies in their means of production and transmission, if any part of the grid system fails, then it can cause regional scale power outages, such as the one that happened in Texas after a snowstorm in February 2021 (Council on Foreign Relations [Cfr], n.d.). Due to this, a shift towards decentralized local power networks, such as self-sustaining community microgrids, has begun to occur. While this distributed form of power generation and transmission has been on the rise with the increase in 'green' energy production, the microgrid has taken some of its design from nature itself. A recent biomimetic development of microgrid technology has rooted its basis in the facilitated communication and resource distribution of trees within forest systems via mycorrhizal networks. Microgrid technology mimics this function through the use of IoT-generated smart contracts to create an autonomous energy community.

In these communities, the microgrid behaves as a transactive energy market, allowing all consumers and producers (in a residential context, each home acts as a singular prosumer, an entity that both consumes and produces) to trade electricity through the use of blockchain smart contracts. When one prosumer (a tree in the forest) has an excess of energy, a smart contract is generated by the blockchain mediator (the mycorrhizae) at a lower than market energy rate, and is then sent out to a consumer (another tree in the forest) in need of energy. Both parties are able to approve or decline the monetary energy transaction through an internet based user interface. If the contract is declined by either party, the mediator will either generate a new smart contract, or go to the next prosumer or consumer. In most microgrid models, low-energy use is incentivized by allowing the greatest prosumers to sell their excess energy first, and the lowest consumers to buy said energy first at the lowest rate. This pattern will then go down the line, allowing the next greatest prosumer to sell second, and the next lowest consumer to buy second, and on and on.

Figure 2

Diagram depicting the mirrored functions of microgrids versus mycorrhizal tree-talk

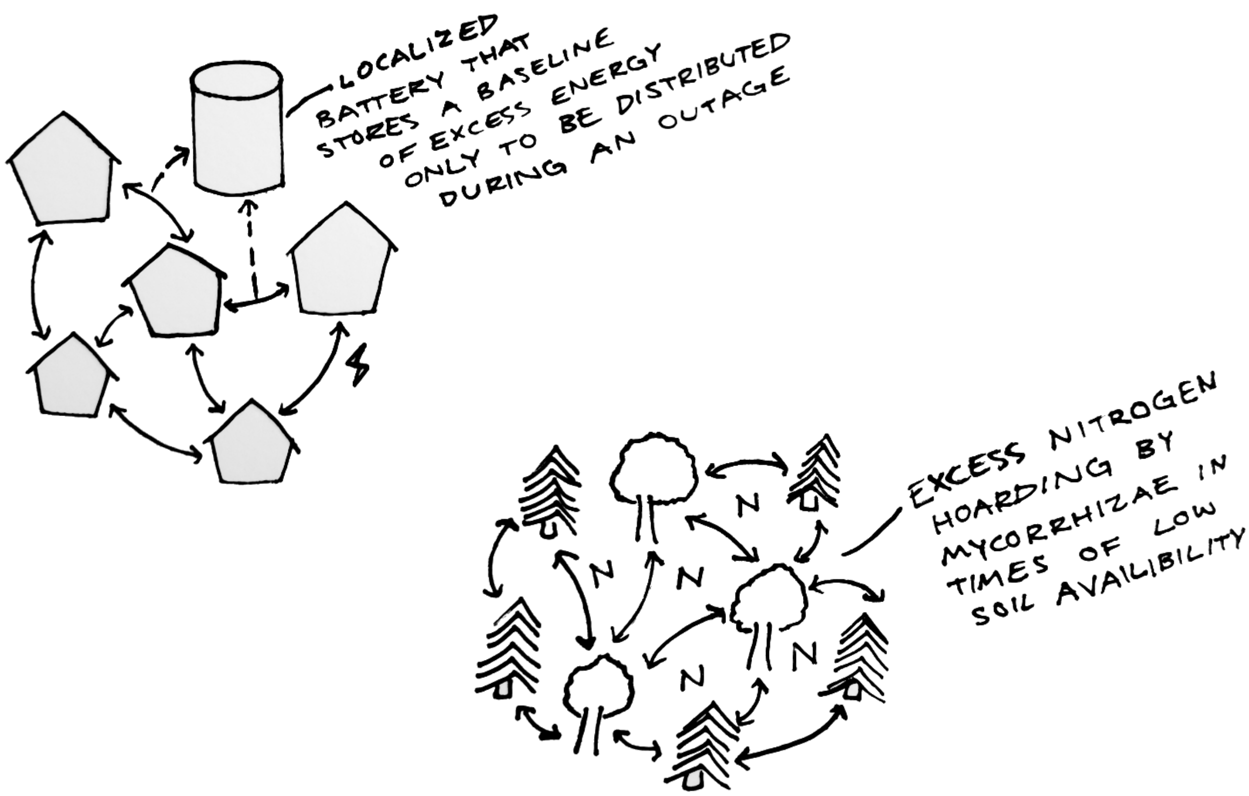


Energy use histories are logged to keep track of efficiency rankings. This power hierarchy is similar to the biological mechanism of mycorrhizal tree communication, as older, *mother trees*, have the largest root network, and therefore the most transactional benefit to the mycelia mediator, granting them the greatest authority in determining where resources are distributed throughout the forest (Beiler et al., 2010).

Further recent studies suggest expanding the microgrid from this established phyto-centric model (one that prioritizes the needs of the consumers and prosumers, *the trees*), to a myco-centric model (one that prioritizes the overall health and needs of the blockchain distribution network first, *the mycorrhizae*). This model, dubbed the *Mycorrho-grid*, by Zachary Gould, addresses the larger functioning of the microgrid as a cohesive mechanism through energy storage on a local battery within a centralized system (Gould, 2022). The baseline energy capacity of the battery is always met prior to transacting energy to prosumers. This approach ensures that a backup source of energy will always be available in case of a regular power outage. The backup baseline is adjusted to fit the volume of standard outages that the community has typically experienced. Oskar Franklin's study (et al., 2014) demonstrates that during times of low nitrogen availability within host soil, plants will instantaneously switch over to or favor a mycorrhizal strategy as compared to a non-mycorrhizal strategy for nitrogen obtainment. Plants that have a mutual relationship with ectomycorrhizal fungi are incentivized to produce and export more carbon to the mycorrhizae to ensure that they are prioritized in receiving nitrogen, likewise the ectomycorrhizal fungi is incentivized to increase nitrogen uptake to export back to the plants. This results in the host soil to be further depleted of nitrogen, as the mycorrhizae has excess nitrogen stored for transactional use. While both the mycorrhizae and its beneficiary plants go through a period of heightened carbon and nitrogen production, they both still profit from the transaction and have their nutrient needs met. For plants that have not formed symbiotic relationships with the ectomycorrhizal fungi, the soil based nitrogen market becomes scarce and if not competitive enough, can suffer from a nitrogen deficiency. In the model of a community microgrid, this would translate into a greater resilience for homes linked into the transactional energy network during a power outage event. Homes that are not linked to the microgrid would fail to receive the excess electricity (nitrogen), while homes that are active prosumers in the network would be given some of the electricity stored in the microgrid reserves.

Figure 3

Diagram depicting the comparison between localized microgrid energy storage and mycorrhizal nitrogen hoarding during times of scarcity



This idea of resilience within microgrids is one of the newer developments based on Gould's simulated *Mycorrho-grid* model. As mycorrhizal networks build up a portfolio of different tree species within a forest to increase their biodiversity and therefore their resilience in the event of a species specific virus or crisis, microgrids could also increase their resilience by creating a mixed-use energy district (Gould et al., 2020). While common mycelial networks can span as far as the mycelium can grow based on its partnered plant network, an efficient mixed-use microgrid would base its size on an appropriate portfolio of diversified prosumers. By integrating residential, commercial, and other building types (such as hospital campuses or industrial parks) together under one microgrid, while keeping the microgrid truly at a *micro* scale to prevent the same issues caused with the centralized regional power grids currently in the United States, then the system would have more options for energy production and transmission. Due to the load diversity in both consumption and production, the microgrid could operate on behalf of the overall health and resilience of the system, and be able to prioritize certain prosumers such as hospitals in times of power crises.

Many of the challenges that the current microgrid model faces are rooted in the technological methodology of the systems. To explain, a large amount of recent simulated microgrids operate on cryptocurrency as the monetary exchange between prosumers within the system. As the regional grid system operates on United States Dollars (USD), making a true economic comparison between the two systems incompatible. The majority of the United States population utilizes USD for their daily transactional exchanges, and cryptocurrency is not financially, or intellectually available to everyone, making it an unfair currency to use when negotiating a basic shelter need such as electricity. Without a standard currency being universal on the microgrid user interface, microgrid communities could inadvertently become exclusive to those with access to resources to spend and understand cryptocurrency. In order to implement self-sustaining microgrids nationwide, this is an issue that would need to be addressed. Additionally, many current built and simulated microgrids also operate on solar technology, and while solar panels have advanced dramatically in the past decade in terms of efficiency, producibility, and scale (Nayak et al., 2019), they still have logistical restrictions in terms of initial cost and efficiency in locations with subpar climate conditions.

Aside from the limitations of blockchain and solar based technologies themselves, perhaps one of the greatest potential failures of mycorrhizal modeled microgrids is the lack of a truly mutualistic form of symbiosis between the grid prosumers (homes) and the blockchain mediator. In typical mycorrhizal forest and plant networks, the fungi is directly benefitting from the transactional network, as are the connected trees. Yet in ‘mycorrho-grids’, while the prosumer homes (trees) benefit from the relationship through being able to barter with other prosumers in the market, the blockchain mediator (mycorrhizal fungi) fails to receive a tangible reward of any form. The only incentivization that the blockchain has, has been coded into its nature by force, and that incentive is merely to keep existing in order to be able to run smart contracts and complete the tasks it was manufactured to do. In order for the microgrid to develop into a truly autonomous energy system, then the blockchain mediator would have to become in some sense, self-acting. Mycorrhizal forest networks work because both the forest and the fungi choose to work together in order to benefit each of their own long term self-preservation. While they act in mutualism, they both use the symbiotic relationship as a self-serving mechanism.

Critical Analysis Focus Area 2: *Industrial Symbiosis*

Since Frosch and Gallopoulos's seminal work on *industrial ecosystems* as a way to optimize strategies for manufacturing (1989), *industrial symbiosis* has emerged as a sustainable way of organizing our production and waste cycles. Chertow (2000) has developed industrial symbiosis based on the original concept of industrial ecosystems, which use waste from one industrial process as a component for another industrial process. Much like forest ecosystems and mycorrhizal networks, these industrial ecosystems, if complex enough, can function as a wholly circular economy, leaving little to no waste in a cyclic process. Industrial symbiosis refers to this mutually beneficial, low waste transaction that occurs between separate industrial entities, creating a symbiotic relationship between them, and when placed in close geographic proximity, can create a larger circular, symbiotic network. When an industrial ecosystem can become circular, industrial symbiosis is achieved.

One study reviews the evolution of the industrial symbiosis organization in Sotenas, Sweden, as a case study on the management of water resources and wastewater treatment through preliminary lifecycle assessments completed in an attempt to reduce waste across disciplines, by means of redistribution. With further plans in place to add renewable energy, food production, aquaculture, algae production, marine technology, and upcycling waste heat and fish industry waste from the neighboring sea to create products, this proposal brings the circular style economy of a biological ecosystem fully into play. The network already includes several fish processing industry entities, algae production, a plastic sea waste recycling system, and a land-based salmon farming business (Martin & Harris, 2018).

Industrial symbiosis is essentially a responsible means of supply chain collaboration between industries. By creating a system that manages and recycles or redistributes waste and excess utilities, cities and networks can become a lot more sustainable through resource efficiency. This concept also is beneficial from a social perspective, as it boosts regional development and a sense of community (Herczeg et al., 2017). And it is this social component that is so important in an altruistically acting autonomous energy system. If the operators (people) can support actions that benefit the whole of the system, then the industrial ecosystem can closer mimic a natural ecosystem, where mutual partnerships can determine longevity and survival, such as in low nitrogen periods for mycorrhizal interacting tree species.

This requirement of human input to initiate the industrial symbiosis cycle however, is the largest limitation in moving the theory forward (Chertow, 2000). Nature has had millions of years to self-organize, form, test, and adapt what are now successful ecosystems, and they are still evolving with factors such as human intervention and climate change. So for humans to try to manufacture the industrial equivalent of an ecosystem within just a few years of planning and organization, the task is monumental. Accounting for each and every nuance that a self-sustaining ecosystem needs to function properly and maintain symbiosis, is something that takes huge efforts of careful observation and inter-disciplinary research across the involved industries. Aside from this, industrial ecosystems are not truly autonomous and self-healing; biological ecosystems are able to respond and regenerate to changes within their environment, industrial ecosystems require forced intervention to adapt to a system component failure or material shortage. Lastly, industry is a business, and like any business, it can fail. So if one of the integral industrial entities fails economically, or suffers a period of lower production, then the entire industrial ecosystem could become comprised. Without backup entities in place to take over the open or reduced role, then symbiosis is lost. In an attempt to reduce these losses, unified network utility analyses can be used to help generate the first connections within a potential industrial ecosystem. This analysis method assesses mutual relationships between individual nodes (parts of the city or industrial entities) and highlights potential mutually beneficial relationships (Fan et al., 2017).

Recent studies also suggest that this lack of resiliency can be improved by implementing higher amounts of involved industry entities and resource exchanges between businesses (Zhu & Ruth, 2013). Much like mycorrhizal networks, diversity of partnerships within the system creates greater collective resilience. The more exchange options that each entity has, the less vulnerable the system will be to an unforeseen failure, because each entity will have at least one alternate transaction pathway to choose from. Unlike the hierarchy that is created in microgrids and with mother trees in mycorrhizal forest networks, for industrial ecosystems, resilience increases when there are not preferred prosumers within the network, because if certain entities are given preferential rights to transaction, then competition decreases, and therefore the diversity of exchanges decreases.

Open Research Challenges: *Hardwired vs. Biological/Organic Systems*

While the most common study of mycorrhizae that takes place today examines the connection between fungi and trees, mycelia have been around for far longer than this forest economic model we have based energy microgrids off of. While we have been attempting to modify our mechanical systems to replicate the transactions that mycelium facilitates within forest ecosystems, research on physically adapting mycelium networks to complete these transactions within a built environment is largely unexplored. With CRISPR technology continuing to evolve, and genetic modification of plants and fungi becoming more accessible in the mainstream, it is not so far off to think that mycorrhizae could be the future of our building methodologies.

Dead, compacted mycelium block has been recently discovered to be an industrial level strength, highly fireproof, well insulated, and acoustically sound building material for load bearing walls (Oral et al., 2022), but some scientists are now looking to see if these walls can be made out of live mycelium that can adapt, heal, and generate autonomous decisions through the implementation of polymer nanoparticles that act as electronic sensors capable of instructing computational control (Adamatzky et al., 2019).

Mechanical and electrical technologies have the potential to fail. This has been evident since the discovery of electricity, and in the United States alone, we have seen a substantial increase in the occurrence of power outages as weather events become more extreme (Whitehouse, n.d.). One outage, the *Northeast Blackout of 1965*, caused a full electricity grid collapse all the way from Ontario, Canada, to New Hampshire, including the cities of New York City and Buffalo, New York, and affected a total of seven states. The entire Northeastern coast was halted to a stop until power was restored, and it was all caused by a singular faulty relay in a substation in Ontario that created a domino effect (Baruch, n.d.). While microgrids help solve the issue of an overly large, centralized power grid that can be wiped out due to the failure of one part, and allow for decentralized control in autonomous communities, each microgrid is still susceptible to localized failure in the event of a blackout. Blockchain requires both electricity and access to the internet in order to function properly. In the event that a power outage were to take place in the microgrid, the blockchain transaction system itself would not be able to facilitate any transfer of energy, and a mechanical backup system would be required.

Blockchain is record based ledger system of transactions, and it runs on smart contracts, which are created through series of consensus algorithms that are agreed upon by the distributed nodes within the network. While it is claimed that blockchain is a relatively safe algorithm technology, it is still in its relative infancy, and any algorithm has the potential to fail. In the stock market crash of 2008, a faulty computer algorithm called the Li Guassian copula caused the surplus in lending of subprime mortgages which eventually led to the collapse (Mohti et al., 2019).

Organic systems, such as the relationship between fungi and plants, has spent years evolving to become resilient in this nature. If we could model our building technologies by utilizing these living organisms instead of simply mimicking them, then we could possibly tap into this resilience as well. Our buildings could adapt for us because they are actually an autonomous living organism. This is not to ignore however, the decreased resilience of natural systems in the time of human presence on Earth. As we continue to industrialize, entire forests and ecosystems are destroyed by our technology through both intentional practices, such as logging, and unintentional consequences such as chemicals entering our water systems through improper disposal of everyday goods. Perhaps some type of hybrid model, like Adamatzky's electronically enhanced mycelium structures, may be a better model for biomimetic design.

Summary: Findings and Future Projections

Mycorrhizal networks facilitate interplant communication between trees, giving them the ability to 'talk' to one another, sending resources, nutrients, and allelochemicals via hyphae connections. Due to this high level of interconnectivity within forests, tree-partnering mycorrhizae play a major role in the circular economy of the ecosystem, supporting cyclic growth and death of each living entity. Industrial symbiosis within industrial ecosystems mimics this biological circular economy, and energy microgrids have modeled blockchain transactional behavior on the forest communication that is facilitated by mediating mycorrhizae. While each of these concepts is modeled after mycorrhizal behavior, in order for our built environments to truly begin to mimic the functional processes of interplant communication, then both microgrids and industrial symbiosis would need to be implemented together into one manufactured ecosystem, one *forest*. Microgrids need to be scaled up and see an increase in prosumer diversity, and industrial symbiosis can be scaled down to a smaller, residential community level to see resource lifecycle benefits in other sectors in addition to the industrial economy. A critical analysis of current mycorrhizae modeled technologies suggest that system diversification is the next step to integration, and the limiting factor of manmade technological failure suggests moving to a hybrid bio-engineered model for future research.

References

Adamatzky, A., Ayres, P., Belotti, G., & Wösten, H. (2019). Fungal Architecture Position Paper. *International Journal of Unconventional Computing*, *14*. Arslan, G. Y. (2014). Biomimetic architecture a new interdisciplinary approach to architecture. *ALAM CIPTA, International Journal of Sustainable Tropical Design Research and Practice*, *7*(2), 29-36.

Baruch. (n.d.). *NYCdata | Disasters*. https://www.baruch.cuny.edu/nycdata/disasters/blackouts-northeast.html.

Beiler, K. J., Durall, D. M., Simard, S. W., Maxwell, S. A., & Kretzer, A. M. (2010). Architecture of the wood-wide web: Rhizopogon spp. genets link multiple Douglas-fir cohorts. *New Phytologist*, *185*(2), 543-553.

Cfr. (n.d.). *How Does the U.S. Power Grid Work? | Council on Foreign Relations*. https://www.cfr.org/backgrounder/how-does-us-power-grid-work.

Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy. *Annual review of energy and the environment*, *25*(1), 313-337.

Eason, W. R., Newman, E. I., & Chuba, P. N. (1991). Specificity of interplant cycling of phosphorus: the role of mycorrhizas. *Plant and Soil*, *137*(2), 267-274.

Fan, Y., Qiao, Q., & Chen, W. (2017). Unified network analysis on the organization of an industrial metabolic system. *Resources, Conservation and Recycling*, *125*, 9-16.

Francis, R., & Read, D. J. (1984). Direct transfer of carbon between plants connected by vesicular–arbuscular mycorrhizal mycelium. *Nature*, *307*(5946), 53-56. Franklin, O., Näsholm, T., Högberg, P., & Högberg, M. N. (2014). Forests trapped in nitrogen limitation–an ecological market perspective on ectomycorrhizal symbiosis. *New Phytologist*, *203*(2), 657-666.

Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for manufacturing. *Scientific American*, *261*(3), 144-153.

Gould, Z. M. (2022). *A mycorrhizal model for transactive energy markets* [Unpublished doctoral dissertation]. Virginia Polytechnic Institute and State University.

Gould, Z. M. I., Day, S. D., Reichard, G., Dimobi, I., & Choudhry, A. (2020, March 4-6). *The Mycorrho-grid* [A Blockchain-based Mycorrhizal Model for Smart Solar Microgrids]. 2020 Residential Building Design & Construction Conference, Penn State University, University Park, PA, USA. PHRC.psu.edu

Herczeg, G., Akkerman, R., & Hauschild, M. Z. (2018). Supply chain collaboration in industrial symbiosis networks. *Journal of Cleaner Production*, *171*, 1058-1067.

Martin, M., & Harris, S. (2018). Prospecting the sustainability implications of an emerging industrial symbiosis network. *Resources, Conservation and Recycling*, *138*, 246-256.

Mohti, W., Dionísio, A., Ferreira, P., & Vieira, I. (2019). Contagion of the subprime financial crisis on frontier stock markets: A copula analysis. *Economies*, *7*(1), 15.

Nayak, P. K., Mahesh, S., Snaith, H. J., & Cahen, D. (2019). Photovoltaic solar cell technologies: analysing the state of the art. *Nature Reviews Materials*, *4*(4), 269-285.

Oral, H., Karakışla, A., Kadakal, B., Özmen, D., Korkmaz, E., Deniz, İ., & Kavaf, S. (2022, May). MYCO-HILLS: AN EXPERIMENTAL RESEARCH ON MYCELIUM BASED BUILDING BLOCKS.

Simard, S. W., Perry, D. A., Jones, M. D., Myrold, D. D., Durall, D. M., & Molina, R. (1997). Net transfer of carbon between ectomycorrhizal tree species in the field. *Nature*, *388*(6642), 579-582.

Smith, S. E., & Read, D. J. (2010). *Mycorrhizal symbiosis*. Academic press.

Whitehouse. (n.d.). *A White House call for real-time, standardized, and transparent power outage data | OSTP | The White House.* https://www.whitehouse.gov/ostp/news-updates/2022/11/22/a-white-house-call-for-real-time-standardized-and-transparent-power-outage-data/.

Zhu, J., & Ruth, M. (2013). Exploring the resilience of industrial ecosystems. *Journal of environmental management*, *122*, 65-75.