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**Research Paper**

# How Forest Trees Share Sugars and Signals Through Underground Fungal Networks

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***Abstract***
*Underneath the soil of nearly every forest on Earth there's this complicated web of fungal filaments, tying together tree roots across generations, and often across multiple species too. People call these mycorrhizal networks the "wood wide web" and they work like some sort of buried infrastructure for forest life, helping move carbon, nutrients, water, and even chemical signals about stress between plants. The partnership between trees and mycorrhizal fungi is very old, stretching back over 400 million years, and it shapes the carbon and nutrient dynamics of land ecosystems on a global level. In the late 1990s, field work by Simard and colleagues showed bidirectional carbon passing between paper birch and Douglas-fir via shared ectomycorrhizal networks, which pretty clearly suggested that trees from different species can trade photosynthate underground. Since then, researchers have also asked if these same systems can act like a kind of relay for defense signals when trees get hit by herbivores or pathogens, and some findings point to chemical cues moving through fungal hyphae in a matter of hours. Still, the whole topic isn't free of debate, because a careful 2023 review in Nature Ecology & Evolution warned about positive citation bias, and about overreading what these networks do when you zoom out to the ecosystem scale. This piece discusses the biological architecture of mycorrhizal networks, how and how far resources are actually transferred, what the signaling evidence looks like, and what these underground exchanges might mean for forest management, plus climate resilience too.*

***Keywords:*** *wood wide web, carbon transfer, forest communication, mother trees, mycorrhizal networks, ectomycorrhizal fungi, common mycorrhizal network*

## I. Introduction

Walk into an old-growth forest and a lot of what makes that ecosystem so special is basically invisible to you. The canopy is spectacular, sure, but the genuinely complex happening is down below, in a zone just a few centimeters under the leaf litter, where the tips of tree roots and the filaments of soil fungi are always tangled, kind of perpetually entwined.

Most people get taught in school that plants make their own food with photosynthesis and then grab water and minerals from the soil through roots. That sketch is mostly right, but it misses an essential ally. The fungus takes in carbon from the tree, and in return it helps the plant reach water, phosphorus, nitrogen, and other soil resources at a scale that roots alone cannot really manage. Mycorrhizal fungi grow as microscopic threads called hyphae—one thread is thinner than a human hair— and when they're gathered together, they become mycelium, an underground body that branches and can travel through soil as mats, fans, cords, and threads.

What makes this partnership remarkable isn't just what it does for individual trees. When different trees end up sharing compatible fungal partners, those partners can build sort of physical pathways that link multiple root systems, and then things start to happen. More than 90% of all land plants live in close symbiosis with fungi, the mycorrhiza. For a long time, mycorrhiza was treated like an interaction between two partners, a plant and a fungus. Still, there are now indications that forests in particular might be threaded through with entire networks of plant roots and fungal tissue. In this picture, plants aren't merely separate actors, they can actually share resources, and possibly even messages, across distances, mediated by common fungal associates.

This article then walks through what those exchanges really involve, how confident scientists are for each claim and detail, and why any of this matters for the way we think about, and manage, the forests that cover roughly 31% of the world's land surface (FAO, 2020).

## II. The Biology of the Partnership

### 2.1 Ancient Roots and a Global Footprint

The relationship between plants and mycorrhizal fungi isn't some new evolutionary odd thing. For over 400 million years now, mycorrhizal fungi and plants have been, pretty much, hanging together in a partnership that ends up being crucial for how global ecosystems emerge and keep working. And if you try to picture the timing, those interactions show up roughly 200 million years before the dinosaurs and they were already kind of locked in well before the first forests really appeared on land. Many botanists think the move onto land by plants wasn't feasible without this help, meaning mycorrhizal fungi made it easier for early plants to reach mineral nutrients from bare rock, long before anything like modern soil showed up, or even existed.

Nowadays the footprint is staggering, like in a straight up measurable way. Arbuscular mycorrhiza (AM), ectomycorrhiza (EcM), and ericoid mycorrhiza (ErM) colonize more than 85% of vascular plants across basically all vegetated terrestrial biomes. The carbon part is… especially huge. Global plant communities' channel about 3.93 Gt $CO_2e$ per year into arbuscular mycorrhizal fungi, and another 9.07 Gt $CO_2e$ per year into ectomycorrhizal fungi. Those numbers are such a large share of the carbon that photosynthesis captures, and then routes underground right away— not for building wood, or leaf tissue, but to keep the fungal partner alive, and functioning, day after day.

Two big kinds of mycorrhizal fungi really do matter most for forest trees. Arbuscular mycorrhizal fungi, AM fungi, physically get into plant root cells and they show up with, sort of, the vast majority of land plant species. Ectomycorrhizal fungi, EcM fungi, on the other hand make a dense sheath around root tips, but they do not actually go inside the cells themselves, and they're especially linked with boreal and temperate forest trees — oaks, pines, beeches, firs, and birches being a few examples … those same trees are also the ones most often studied when people talk about underground networking. In exchange for the ability to grab soil nutrients and water, the tree sends sugars and other carbon-based compounds, that are made via photosynthesis, to the fungus. Often the tree can end up dedicating up to 30% of its fixed carbon just to keep that partnership going

That's, honestly, a huge investment. A tree putting 30% of its photosynthate into a fungal collaborator is basically betting that the nutrient and water access it gets back is worth the cost. And since this kind of arrangement has been hanging around for more than 400 million years, that bet seems to have paid off.

### 2.2 The Architecture of a Common Mycorrhizal Network

When one individual fungus, sort of quietly, connects the roots of two or more trees, scientists tend to call it a common mycorrhizal network (CMN). The structure that shows up isn't simple, like not at all. A teaspoon of healthy forest soil can have up to 100 meters of fungal hyphae, and those can form a dense three-dimensional mesh so carbon, nutrients, and various chemical compounds can in principle travel through it. In fact, when hyphae grow extensively and very densely, they end up making a network that reaches something like 10 to 100 meters of hyphae per gram of soil.

But not every fungal filament hooks into the same network. Mycorrhizal fungi differ a lot in how many tree species they can team up with. Some are generalists and they colonize many tree species across a whole stand; others are specialists that work with only one. The generalists matter a lot for creating the long-range linkage that researchers have mapped, and yes, debated for years. In one well known 2010 study, in an old-growth Douglas-fir Forest in British Columbia, Beiler and coauthors mapped the precise architecture of the ectomycorrhizal network. They reported that individual trees were linked to dozens of other trees, and that the oldest, largest trees sat in the most central spots, with more connections touching than basically any neighboring tree (Beiler et al., 2010).

As illustrated in Figure 1 below, the network architecture in a mixed Douglas-fir Forest is not random but scale-free, with dominant hub trees connecting far more neighbors than younger, peripheral individuals.

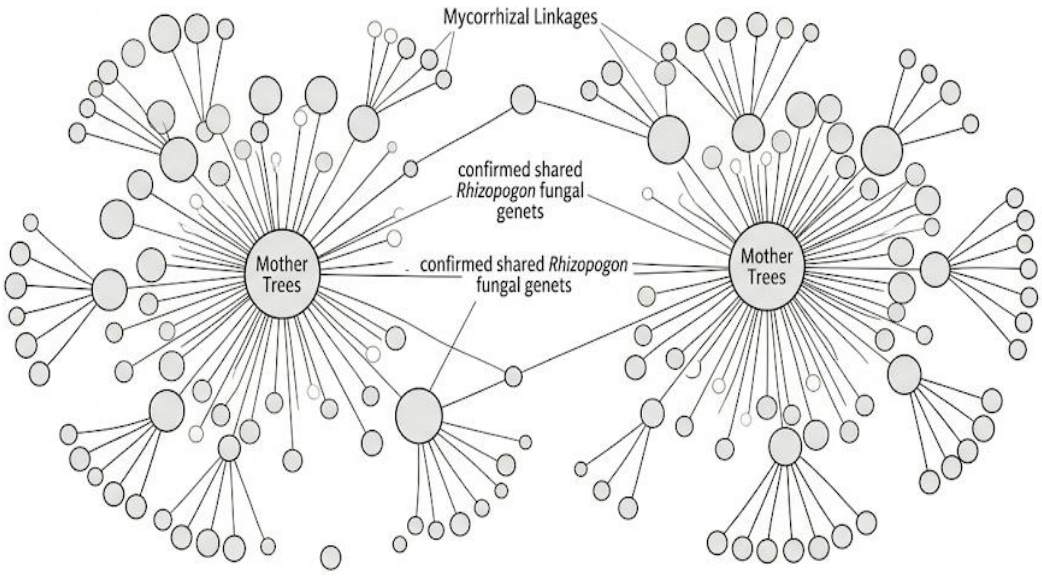


Figure 1: Network Map of Ectomycorrhizal Connections Between Douglas-Fir Trees in an Old-Growth Forest Stand

This conceptual network diagram, drawn from the mapping study by Beiler et al. (2010) in New Phytologist (185: 543–553) kind of shows individual Douglas-fir trees as nodes. The nodes vary in size, because the size tracks how many fungal connections each tree keeps. You can see thin lines between nodes, those lines stand for confirmed mycorrhizal linkages through shared Rhizopogon fungal genets. The biggest and oldest trees end up in kind of central hub positions with the greatest number of connections, while younger seedlings hang around the outside, with fewer links and less involvement. A main idea, maybe the key insight, is that the layout isnt a simple flat mesh, but more like a hub-and-spoke architecture. In that kind of setup, the very connected "mother trees" could be doing a disproportionate share in the connectivity and resource dynamics across the whole stand. Data sourced from Beiler et al. (2010), New Phytologist, University of British Columbia.

## III. Carbon Transfer: What Moves and How Much?

### 3.1 The Simard Experiments and Their Legacy

The notion that trees might pass carbon, sort of cheekily through fungal bridges, was really bolstered by a famous 1997 field study, led by Suzanne Simard at the University of British Columbia. She and her team worked in a mixed wood of paper birch (Betula papyrifera) and Douglas-fir (Pseudotsuga menziesii), out in British Columbia. Simard along with colleagues used radioactive carbon isotopes— carbon-14 and carbon-13— to map the actual movement of photosynthate between neighboring trees. They put seedlings inside plastic enclosures, bags really, filled with isotope labeled $CO_2$, waited nine days, then checked where that labeled carbon had gone.

With reciprocal isotope labeling done right there in the field, bidirectional carbon exchange between the ectomycorrhizal tree species Betula papyrifera and Pseudotsuga menziesii was shown. This led to a net transfer of carbon, from birch over to fir. And the direction of that net flow wasn't random. When Douglas-fir seedlings were shaded and therefore making less of their own photosynthate, more carbon traveled from the sunlit birch toward the shaded fir. Flip the conditions, meaning reverse the setup so fir could make more and birch less, and the direction of net flow also flipped. So it looked like something within the fungal-plant setup was responding to the relative carbon situation of linked trees, channeling extra carbon toward whichever one was in more need.

Birch can also help Douglas-fir by sharing carbon through mycorrhizal networks, and the more birch shades Douglas-fir, the more carbon it delivers through the mycorrhizal networks. The trees also trade resources seasonally — Douglas-fir shares excess sugars with the leafless birches in spring and fall, and in return the birches provide the Douglas-firs with sugars in summer.

This seasonal give-and-take is one of the more elegant observations in basically the whole field. Two tree species with different leaf timing — one deciduous, one evergreen — seem to balance each other's off-season, through a shared fungal network. It is not hard to see why this story caught the public imagination, in an almost unexpected way. From far away it looks, like mutual care, like somebody actually meant it.

Evidence that the blueprint, of mycorrhizal networks, has been mapped and that CMN carbon sharing from mature trees to seedlings has been shown has led people to say that trees in forests are more intertwined than we once believed. After that, over the next two decades, more studies branched out, and they covered other forest kinds, more tree species, and wider regions. In nearly all cases, they kept reporting the same pattern labeled carbon can move between trees via shared fungal networks.

### 3.2 Mother Trees and Hub Dynamics

The phrase "mother tree" basically points to those huge, long-lived, very well-connected trees that sit at the center of mycorrhizal networks. Simard helped make the idea known, in both the scientific literature and, though more controversially, in her 2021 memoir plus some popular science pieces.

These very connected hub trees, sometimes described as mother trees, can pass surplus carbon and nitrogen through the mycorrhizal network to seedlings growing below them, and that can nudge up seedling chances of making it. A few studies even propose that the biggest resource handoffs, tend to go to their direct offspring— seedlings that are genetically tied back to the hub tree. Still, whether this counts as actual kin-recognition, or it's more like cause-and-effect from closeness and network placement, is very much debated right now, in active ways.

As for the carbon transfer evidence, in real forest settings, it's fairly sturdy in several studies. For example, in a tightly controlled setup, Teste and collaborators reported that Douglas-fir seedlings with access to mycorrhizal networks did notably better, surviving more than seedlings that were kept isolated. The advantage showed up especially when drought stress was part of the conditions (Teste et al., 2009). Even so, the scale of that carbon boost and how important it was, didn't behave the same across different scenarios, which makes it hard to jump to neat blanket conclusions.

## IV. Signals in the Dark: Chemical Communication Through Fungal Pathways

### 4.1 Herbivore Attacks and Underground Warnings

Beyond carbon, and nutrients, something more surprising might travel through mycorrhizal networks: information. When a plant gets attacked by an insect or it gets infected by a pathogen, it often flips on a suite of chemical defenses. The question that researchers started asking in the early 2010s was kind of simple but also a bit strange, like can connected plants get a warning via the fungal network and then gear up their own defenses before they are attacked themselves.

Stress signals have been shown to move from injured plants to healthy ones through mycorrhizal networks even faster than carbon, nutrient flow, or water. Herbivore- and pathogen-induced stress responses were observed as up-regulated in undamaged neighbors in as little as 6 hours after insect or fungal infestation of the donor plants, when those donors were linked through arbuscular mycorrhizal fungal networks.

Six hours is fast. For comparison, the transfer of meaningful amounts of carbon between trees can take days, or weeks. The speed of this signal transfer implies it's not the same slow, diffusion-like movement we associate with carbon and mineral nutrients. Researchers propose that jasmonate, which is a plant hormone tied to defense activation, may travel along the hyphal network and then switch on defense genes in nearby trees well before any real attack shows up.

There is increasing evidence that mycorrhizal networks can transmit herbivore- or pathogen-induced defense signaling compounds to warn neighbors of pest infestations, kin recognition signaling compounds to communicate genetic relationships of neighbors, and toxins such as allelochemicals.

In this kinda striking experiment with Douglas-fir and ponderosa pine trees, Song and Simard's team… defoliated the Douglas-fir, as if a budworm was really attacking, and then they noticed more defense signaling kicking in within nearby ponderosa pines. Those particular pines were connected through the ectomycorrhizal network, while the others weren't really part of the same route. So the connected pines basically turned up defense-related genes, but the unconnected control pines stayed more or less the same. That led them to conclude that info about the defoliation event was getting carried along through the fungal network (Song et al., 2015).

Then there's another piece, aphid herbivory can trigger interplant signaling via mycorrhizal networks too, functioning kind of like an "early warning system" to neighboring plants. It does that by nudging changes in the volatile organic compound profiles of both the plants that are being eaten and also the neighboring plants that are not. The end result is a community-wide boosted defense response, like the whole neighborhood gets alerted at once.

And honestly, this is genuinely remarkable science. An organism getting eaten, and still somehow warning its network-connected neighbors to get ready— it almost reads like science fiction, you know, like from a different world.

### 4.2 What the Fungi Get Out of It

It's worth taking a moment here, to ask a question that's easy to overlook: what do the fungi themselves actually get out of any of this? The networks are not cables the trees laid down for their own convenience, or something like that. They're living fungal organisms with their own evolutionary goals, even if we humans keep picturing it as a neat service line.

Researchers worked out, sort of theoretically, that plant warning signals are rarely evolutionarily stable. There are two viable possibilities that could line up with what researchers see in the data. First, when a plant gets attacked, the resulting warning cue becomes too costly for the attacked plant to suppress. Second, mycorrhizal fungi can keep track of their host plants: they detect when a host is attacked, and then they signal that information so other plants in their network also get alerted.

That second possibility, that the fungi act like both monitors and broadcasters, matters a lot. It shifts the story away from trees cooperating with each other and toward fungi maintaining and safeguarding the health of their plant partners. Because when hosts are thriving, they're better suppliers of sugars. In this reading, the fungi aren't altruistic middlemen for tree cooperation. They're more like self-interested managers of a living plot they can't really afford to lose.

It's a subtle distinction, but scientifically it's important. It doesn't make the whole phenomenon any less extraordinary. It just changes the explanation of what's going on, and also why it would evolve in the first place.

## V. The Debate: Science, Nuance, and Popular Narratives

### 5.1 Where the Evidence Is Solid

The science behind mycorrhizal networks goes across a huge range of claims, and it is important to sort out what is pretty settled from what still stays debated. On the solid side, you have mycorrhizal fungi making real connections that link multiple trees in forests. Through these links, Carbon, nitrogen, phosphorus and water can all move, even if people describe it in slightly different ways. Carbon exchange across shared mycorrhizal networks was shown quite a long time ago in lab settings, over half a century actually, and later it was checked in the field too. In the last few years there has been a lot of progress in this general direction, including more signs that carbon transfer might matter ecologically.

At the same time, the signal transfer experiments are also fairly well replicated, in the lab and in controlled greenhouse conditions, especially when you look at arbuscular mycorrhizal systems with herbaceous plants and some tree species.

### 5.2 Where Scientists Push Back

The popular narrative, where trees somehow, deliberately nurture their seedlings and even generously warn one another of danger via a cooperative underground "internet", has lately drawn major scientific pushback. A 2023 review in Nature Ecology & Evolution by Karst,Jones, and Hoeksema says that the stories you see in popular outlets about common mycorrhizal networks, are basically detached from what we can actually show. They also claim that a kind of slant toward citing positive effects of CMNs has, over time, grown inside parts of the scientific literature.

More specifically, Karst et al. argued that field studies give results that are all over the map, with so many competing explanations that it's hard to make confident, broad claims about redistribution of resources that could reliably boost seedling performance in real forests. They also point out that the idea mature trees preferentially funnel resources and defense messages to their offspring through CMNs, still lacks peer reviewed, published evidence.

Honestly this reads like a healthy and necessary correction. Science moves forward by doing exactly this sort of careful, critical inspection. The carbon transfer part is real. The signaling effects are real, at least in tightly controlled experiments. Still, whether these processes work at the larger scale, and with the level of intention that popular books and documentaries sometimes suggest, remains a genuinely open question.

As shown in Figure 2, the spectrum of evidence strength across different proposed CMN functions varies considerably, highlighting where scientific confidence is high versus where caution is warranted.

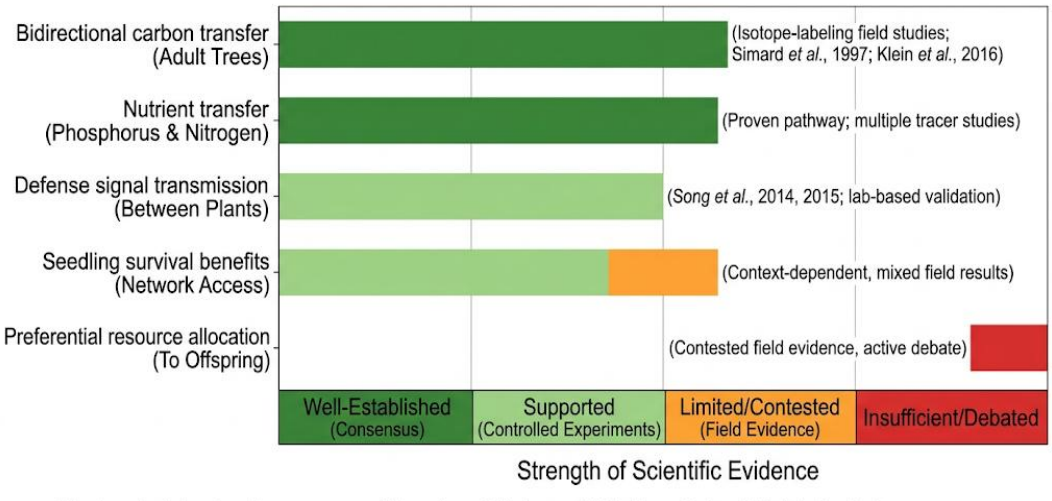


Figure 2: Evidence Strength for Different Proposed Functions of Common Mycorrhizal Networks in Forest Trees

So, uh this horizontal bar chart kind of compares the overall strength of scientific evidence that backs five keys proposed CMN functions: (1) carbon moving both ways between mature trees, (2) nutrient exchange including phosphorus and nitrogen, (3) defense signal transmission between linked plants, (4) seedling survival that benefits from network access, and (5) preferential resource allocation towards offspring trees. The evidence bars go from "well-established" for carbon and nutrient transfer, based on isotope-labeling field studies (Simard et al., 1997; Klein et al., 2016), then move to "supported by controlled experiments" for signal transmission (Song et al., 2014, 2015) and finally end at "contested or insufficient field evidence" for the idea of preferential offspring support.

This figure pretty much pulls together the assessment by Karst, Jones & Hoeksema (2023, Nature Ecology & Evolution) along with what Klein et al. (2023, Frontiers in Forests and Global Change) reported, so you can see where the scientific community seems aligned, and also where there's still active disagreement, like actually continuing debate.

## VI. Implications for Forest Management and Climate Resilience

### 6.1 Why This Matters in a Warming World

Even when you set aside the disputed claims, what is firmly established about mycorrhizal networks has this profound practical implication, kind of like it won't let you ignore it. Forests managed without regard for fungal networks are basically forests managed with incomplete information. So, take clearcut logging for example, it doesn't just remove trees — it also destroys the fungal networks those trees relied on, and also that helped keep things stable. And then when you replant seedlings into soil where established networks have been severed, those young plants end up with a measurable disadvantage, compared to seedlings that can tap into pre-existing hyphal webs.

Experiments have shown that keeping older trees, along with their extensive networks, can reduce loss of carbon from the ecosystem, both above-ground and below-ground. The Mother Tree Project is testing how different retention levels, of mother trees could protect existing carbon pools.

Climate change makes this even more urgent. Connected forests are better able to cope with climate change, and they can remain productive, healthy, and diverse, around for many more generations. The logic feels almost intuitive: a forest where trees can share resources during drought, fire, or pest outbreaks is more resilient than a forest where every tree has to survive entirely on its own.

About 75 percent of terrestrial carbon is kept belowground, and mycorrhizal fungi are basically positioned at a key doorway where carbon enters the soil food webs. So protecting, or even restoring mycorrhizal diversity is not only some ecological principle, it is also a practical maneuver for keeping the carbon sequestration ability of forests on track. Changes caused by people have shifted and, in many places, reduced ectomycorrhizal plants and their partners, which could then ripple through to terrestrial carbon pools.

### 6.2 Practical Applications and Restoration

The implications creep into forest restoration science, sort of indirectly but still, yeah, it's there. Inoculating nursery seedlings with compatible mycorrhizal fungi before planting has become standard practice in some reforestation programs, basically to make sure the young plants don't arrive into the field as total

outsiders. The notion is to give seedlings a head start, by establishing these fungal collaborations early rather than waiting for the seedlings to meet compatible fungi in degraded soil and, sometimes that meeting just never happens.

Past the planting of individual trees, there's rising interest in using network architecture knowledge to steer which trees to keep during selective logging operations. If hub trees — the highly connected older individuals — have a disproportional role in network connectivity and resource movement, then removing them in a careless, blanket way could split the forest's underground communication infrastructure. That kind of split, can ripple into how well the whole stand recovers.

Plant–mycorrhizal associations, which act like connectors between aboveground and belowground biodiversity, can improve both carbon storage and forest multifunctionality. Putting the functional traits of plant–mycorrhizal associations into restoration strategies offers a route to respond to those tangled biodiversity and climate emergencies at the same time, not as separate tasks.

The snag is that practical forest management needs clear and generalizable rules. Meanwhile the science of mycorrhizal networks is still producing those rules, slowly and unevenly. Managers cannot wait until every hypothesis is fully settled before deciding which trees to cut, and which to spare. Still, the current consensus — keep old, connected trees where possible; avoid practices that devastate soil fungal communities; inoculate replanted seedlings — feels reasonable even with scientific uncertainty hanging around.

## VII. Conclusion

Under the forests of the world, there is an old, kind of partnership between plants and fungi that makes physical links, which lets carbon nutrients water and also various chemical signals get passed around between trees in ways most of us never really imagined. The simple gist of these so called common mycorrhizal networks is now, beyond serious doubt, shown by years and years of isotopic labeling tests, molecular mapping work, and tightly controlled signaling experiments. Still, what science is working through is the actual ecological weight of it all in real, messy forests, like whether the carbon that moves between big mature trees and younger seedlings is enough to truly change survival outcomes, and also whether the warning signals that travel along hyphae in lab style setups do anything at scales that matter inside old growth forests.

What is already certain, carries major implications anyway. Mycorrhizal fungi collectively take in billions of tonnes of carbon from the world's plants each year, and the networks they build act as a crucial piece of forest carbon behavior, plus ecosystem resilience. And management actions that tear these networks up — clearcut logging, heavy soil disturbance, removal of all old trees — end up damaging something we are only starting to understand, and it isn't just a small local detail.

The most honest summary of the science might be this: forests are not quite what they appear to be from above. The trees aren't isolated competitors, each fending for itself. But they are also not exactly a network of altruistic cooperators sharing resources with noble intention. What they are instead is something stranger, and more engaging—living things tightly bound to fungal partners in relationships that serve multiple purposes at once, producing patterns of exchange that look, to human eyes, uncomfortably like community. Understanding this sort of community more deeply is among the most important tasks in forest science today, even if we'd rather simplify it.

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