

The Invisible Network

Fungi, Mycelium and Mycorrhiza —

the hidden life beneath our feet



The mycelial network beneath a forest — made visible.

A brochure by OpenMycoNet

openmyconet.de

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Foreword

This brochure is written for anyone who has ever wondered what actually happens beneath a forest. Not up in the canopy. Not in the trunks. But down below — in the dark, hidden, in the soil.

The answer is more astonishing than most people suspect. And more important than we long believed.

We are not a research institute. What we have is curiosity, measurement technology, and the conviction that citizens can make a genuine contribution to science — if the tools and methods are right.

OpenMycoNet is a citizen science project. We record electrical activity in fungal and mycorrhizal networks — at many sites and over extended periods. We want to find out which reproducible patterns can be identified, and how they relate to the respective environmental conditions. The measurement data intended for research is made openly available.

This brochure is the beginning of the story. Read it, ask questions — and if you like: join in.

1 A Forest, a Step



Beneath every step in the forest: a world we barely understand.

Imagine you are standing in a forest.

Perhaps a beech forest in the Eifel. Perhaps a pine forest in Brandenburg. Perhaps the park at the end of your street, where a few old oaks stand, older than the houses around them.

You take a step. Your foot touches the ground. Leaves, perhaps some moss. Perhaps a small twig snaps.

What you don't see — what no one can see without instruments — is what happens exactly beneath that step. Because right now, directly under your sole, a network of unimaginable density stretches out. Threads finer than a human hair. Not a few. An almost unimaginable number, densely branched through the soil.

This hidden world lives. Fungi grow, react to their environment, and transport substances through their hyphal networks. Through mycorrhiza, many of them are also in close interaction with plants — a partnership whose evolutionary history stretches back hundreds of millions of years.

But let's start from the beginning.

Sources & further reading

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2 What Actually Is a Fungus?



What we see is only the beginning of the story.

When most people think of fungi, they think of food — mushroom pizza, chanterelle cream sauce, button mushrooms at the supermarket. Of the fly agaric in a textbook illustration. Of what shoots out of the ground after rain and vanishes again a few days later.

That's understandable. But it's a bit like equating an apple tree with the apple.

What we perceive as a mushroom — the cap, the stem, the structure we pick or photograph — is not the organism itself. It is its reproductive organ. Its brief appearance at the surface. The fruit.

The actual fungus lives elsewhere. Hidden. Underground. And it is usually many times larger than anything we ever get to see.

A Kingdom of Its Own

For a long time, science classified fungi as plants. Only in the second half of the 20th century did it become clear: fungi are neither plants nor animals. They form a kingdom of their own — the Fungi.

The differences are profound. Plants produce their energy through photosynthesis: sunlight, water, carbon dioxide — and sugar is made. Fungi cannot do this. They have no chlorophyll, no green pigment, no ability to convert light into energy.

Instead, they digest outside their bodies: they secrete enzymes that break down organic material in their surroundings, then absorb the nutrients directly through their cell walls. This makes them nature's great decomposers — the recycling specialists.

Without fungi, a substantial part of the decomposition of organic material would fail to happen. Nutrient cycles would be massively disrupted, and forest ecosystems as we know them could not function.

An Ancient Success Story

Fungi have existed for roughly a billion years. For comparison: the dinosaurs disappeared 66 million years ago. Fungi have far outlived them — and will likely still be here when our own story has long since ended.

Their adaptability is astonishing. Fungi can grow on crude oil, on plastic, near radioactive radiation. Certain melanin-containing fungi have also been studied in highly radioactive environments such as Chernobyl. Experiments show that ionizing radiation can alter properties of melanin and, in certain fungi, influence growth.

But the most remarkable ability of fungi is a different one. It is the ability to form connections.

And that brings us to the actual question: what is the organism that forms these connections?

Sources & further reading

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- Dadachova, E. et al. (2007): Ionizing Radiation Changes the Electronic Properties of Melanin and Enhances the Growth of Melanized Fungi. PLOS ONE.

3 The Mycelium: The Actual Organism



Finer than a hair, longer than any road: the mycelium.

The actual body of a fungus is called mycelium. It consists of hair-thin threads — hyphae — that weave, branch, connect and divide again through soil, wood and leaf litter. If you dig into a patch of forest floor and see white, fibrous structures running through the earth: that is mycelium.

And now comes the first moment worth pausing at.

Numbers That Are Hard to Believe

In a single handful of forest soil — roughly the amount that fills two coffee cups — there can be more fungal threads than roads in a small German town. Lined up end to end, they would add up to kilometres. From two cups of soil.

Fungal hyphae can permeate soils at enormous density. Even small soil volumes can together contain hyphal lengths of many metres to kilometres — depending on soil, site and measurement method.

What these numbers mean only becomes clear once combined with another fact: all of this keeps growing back. Every season, every year. The mycelium is not a static structure, but a living, constantly growing organism.

Problem-Solving Without a Brain

Mycelium has no brain. No nervous system. No central processing site. And yet it behaves in a way that — had we observed it in an animal — we would call intelligent.

Decentralized biological networks can form remarkably efficient structures. A famous example, however, comes not from a fungus but from the slime mould *Physarum polycephalum*. Japanese researchers showed in 2010 that, in an experiment, it formed a network whose structure closely resembled the Tokyo rail network.

Real fungal mycelium also forms adaptive networks in which connections can grow, strengthen or recede. How far such processes can meaningfully be described as “problem-solving” is a subject of

ongoing research.

Such experiments show that complex adaptive behaviour can arise even without a brain or central nervous system. Whether this behaviour is already called “intelligence” depends on how the term is defined.

“The mycelium behaves like a decentralized computer network — without a server, without a centre, but with a capacity for problem-solving that we are only beginning to understand.”

— Andrew Adamatzky, Professor of Unconventional Computing, UWE Bristol

And now that we know what the mycelium is, let's turn to the question of what it does.

Sources & further reading

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4 Mycorrhiza: The Oldest Partnership in the World



The mycelium becomes a partner: mycorrhiza on a plant root.

About 450 million years ago, something decisive happened. The first plants ventured out of the water onto land. The land was barren, rocky, poor in nutrients. And yet these early plants managed — probably because they did not come alone.

They came with fungi, or, more likely: the fungi were already there beforehand.

Fossil evidence shows that the earliest land plants were already closely associated with fungal hyphae. Today we call this connection mycorrhiza. The word comes from Greek: mykes (fungus) and rhiza (root). Fungus-root.

A Trade That Changed the World

The principle is so simple that anyone understands it immediately: both sides give something. Both sides receive something.

The plant supplies the fungus with carbon compounds from photosynthesis. Depending on plant species and conditions, a considerable share of photosynthetically fixed carbon can be transferred to mycorrhizal fungi.

In return, the fungus provides the plant with something it could not achieve alone: access to water and nutrients deep in the soil. Because fungal hyphae are far finer than plant roots, they penetrate soil pores that roots alone could never reach. This gives the plant access to a much larger nutrient volume than it would otherwise have.

Phosphorus is particularly critical here — an element plants urgently need for growth, flowering and fruiting, but one that is often poorly accessible in soil. Mycorrhizal fungi can extract phosphorus from minerals and deliver it directly to plant roots.

Depending on plant species, fungal partner and environmental conditions, mycorrhiza can improve nutrient and water supply and increase resistance to certain stress factors. Under suitable conditions, this can also reduce fertilizer needs.

Two Types, One Idea

Science today distinguishes two main types. Arbuscular mycorrhiza penetrates directly into root cells and forms small, tree-like structures there. This form is older and occurs in roughly 70 to 80 percent of all land plants — including most crop plants such as wheat, maize and vegetables.

Ectomycorrhiza, by contrast, grows around root cells without penetrating them. This form is typical of forest trees — beeches, oaks, pines, spruces. The fungi whose fruiting bodies we know and value — porcini, chanterelle, birch bolete — are ectomycorrhizal fungi.

Two types, one underlying idea: the fungus becomes a partner. And from this single step — this one connection that first formed 450 million years ago — what we today call nature emerged over the course of Earth's history.

“The mycorrhizal symbiosis is, without exaggeration, one of the most important biological processes on Earth. Without it, most terrestrial ecosystems as we know them would not be viable.”

— Toby Kiers, Professor of Evolutionary Biology, Vrije Universiteit Amsterdam

Sources & further reading

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5 The Forest Network: Connections Beneath Our Feet



Connections we long could not see — now measurable.

Mycorrhizal fungi can form connections to the roots of different plants. This raises a fascinating question: can resources also flow between plants through such shared mycorrhizal networks?

Researchers have systematically investigated this question over recent decades. What they have found is fascinating — and should nonetheless be viewed soberly.

What Research Has Shown

Forest ecologist Suzanne Simard used isotope-labelled carbon to demonstrate carbon transfer between ectomycorrhizal plants under field conditions. Which pathways, quantities and ecological significance such transfers have under natural conditions is still under investigation.

She has also observed that certain old, large trees are connected to particularly many other organisms — a kind of hub within the network. The term “mother tree” she coined for this is memorable, but also contested: whether these trees actually help “intentionally,” or whether the carbon transfer is more a physical consequence of concentration gradients, is still debated in science.

That substance transfer between mycorrhizally connected plants has been experimentally observed is well documented. How frequently, to what extent, and with what ecological significance such transfers occur under natural conditions remains a subject of ongoing discussion.

What Flows Through the Network

Besides carbon, there is evidence of further transport: nitrogen and phosphorus — the most important plant nutrients — are delivered by fungi directly to roots. During dry periods, fungal networks make use of moisture gradients in the soil. And there are studies suggesting that, in the case of pest infestation, chemical signals can travel through the network to neighbouring plants, which then produce their own defensive compounds.

Whether and how reliably this works under real forest conditions remains an open question. But that mycorrhizal networks are more than passive pipelines is by now well supported.

Electrical Signals

And then there is something that has only been known for a few decades: electrical activity can be measured in fungal mycelium, and experimental work shows that electrical changes can propagate through mycelial systems.

Since the early 1990s, researcher Andrew Adamatzky of the University of the West of England has studied the electrophysiological properties of fungi. The signals he measures follow patterns — regular pulses that respond to external stimuli. Whether this constitutes a form of information processing, and if so of what kind, is one of the most fascinating open questions in modern biology.

It is this question that especially drives us at OpenMycoNet. Because if fungal networks carry electrical signals, then it should be possible to measure them. Systematically, at many locations, over long periods.

Adamatzky studied electrical spike patterns of various fungal species and, under a communication hypothesis, described recurring structures from which a hypothetical “vocabulary” could be derived. Whether such patterns actually carry information — and if so, what — remains open.

Sources & further reading

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- Mousavi, S.A.R. et al. (2013): GLUTAMATE RECEPTOR-LIKE genes mediate leaf-to-leaf wound signalling. *Nature*, 500, 422–426.

6 What Is at Stake



The same soil — two entirely different worlds.

Up to this point, the story has mainly been fascinating. Invisible networks, electrical signals, million-year-old partnerships. Now it becomes concrete.

Because if these networks are so important — if they transport nutrients, feed plants, hold soils together — then the next question inevitably arises: what happens when we damage them?

Ploughing

Intensive soil tillage can mechanically disturb existing hyphal networks and impair the activity of arbuscular mycorrhizal fungi. How quickly such structures regenerate depends, among other things, on soil, management and the fungal community involved.

In addition, there are fungicides used against plant diseases that can also damage mycorrhizal fungi. And synthetic phosphorus fertilizers: high phosphorus availability can reduce the benefit of the symbiosis for the plant and affect mycorrhizal colonization. How strong this effect is depends on plant species, fungal partner, soil and fertilization.

Soil Compaction

Heavy machinery — tractors, harvesters, forestry vehicles — compacts the soil under its weight. Compacted soil has fewer pores, less air, less water. And therefore markedly worse living conditions for fungal mycelium.

More radical is soil sealing through concrete and asphalt. Beneath a road, a parking lot, a concrete foundation, the soil network is permanently interrupted. No regeneration. No regrowth.

Construction interventions in forest sites — such as foundations, access roads or permanently sealed areas — also alter and interrupt soil structures locally. What consequences such interventions have specifically for mycorrhizal networks depends on the site and the extent of the intervention.

The Invisible Wound

We can see a broken vase. We can count a felled oak. But what a destroyed mycorrhizal network was — that we have so far barely been able to measure.

Continuously and extensively capturing the state of a complex mycorrhizal network before and after an intervention remains difficult to this day. Many changes therefore stay invisible to conventional observation methods.

This is exactly where OpenMycoNet comes in.

Sources & further reading

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- van der Heijden, M.G.A. et al. (2015): Mycorrhizal ecology and evolution. *New Phytologist*, 205(4), 1406–1423.

7 What We Know — and What We Don't Yet



Research also means: knowing your own open questions.

There is a claim one often hears: “Science has proven that mycorrhiza ...” Usually followed by something oversimplified. Something with a true core, but that doesn't quite match the actual state of research.

We want to be more honest about it. Here are the things on which there is broad scientific agreement. And here begin the questions to which no one yet has a good answer.

What We Know Fairly Certainly

1. Mycorrhiza is widespread in terrestrial ecosystems. Depending on definition and the plant group considered, large proportions of land plants form mycorrhizal symbioses.
2. Under certain stress conditions, mycorrhizal fungi can improve the growth and yield of crop plants. However, the strength and direction of the effect depend considerably on plant species, fungal partner, soil and environmental conditions.
3. Substance transfers via shared mycorrhizal connections have been experimentally observed. Their frequency, magnitude and ecological significance under natural conditions remain a subject of ongoing research.
4. Structured electrical activity can be measured in fungi and can change under different conditions. What biological function these patterns serve remains largely open.

Where the Questions Begin

Mycorrhizal fungi are involved in carbon flows between plants and soil — but their role in long-term carbon storage is complex.

How much CO₂ mycorrhizal networks actually bind in the soil is surprisingly unclear. Recent studies show conflicting results: under certain conditions, the activity of mycorrhizal fungi can even accelerate the breakdown of existing soil carbon. The relationships are more complex than the simple formula “more fungi equals more CO₂ storage.”

What is almost entirely missing is the overall balance. Such factors are often studied separately or under strongly controlled conditions. Long-term datasets that jointly capture several of these quantities — CO₂ balance, yield quality and quantity, water use, soil health — at the same site under real conditions are, by contrast, considerably rarer.

A system that stores somewhat less CO₂, but delivers substantially higher yields without synthetic fertilizer and keeps the soil healthy in the long run — can nonetheless be ecologically and economically superior. But this only becomes visible when all variables are considered together.

That is the gap. And that is why we started measuring.

Sources & further reading

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8 OpenMycoNet: A Question That Wouldn't Let Go



A BioComm node in the field: listening to what the soil has to say.

At some point, once you have spent long enough with mycorrhizal networks, a question arises that can no longer be set aside.

If electrical activity can be measured in fungal and mycorrhizal networks, and that activity can respond to different conditions — why aren't we capturing it systematically?

The honest answer: the infrastructure was missing. Professional lab measurements are elaborate, expensive and spatially limited. What has largely been missing so far are permanently operated, spatially distributed measurement networks that capture such electrical activity comparably under different real-world environmental conditions.

So we started building one.

What OpenMycoNet Does

We develop BioComm nodes that capture electrical activity together with relevant environmental conditions. The goal is a standardized measurement platform with which data from different sites and time periods become comparable.

Measurement values are processed according to a defined technical workflow and combined for cross-site analyses. Personal information and precise operator locations are kept separate from the research data.

The initial goal is to find out which reproducible patterns can be identified, and how they behave under different environmental conditions and when a site changes.

The measurement data intended for research, together with the necessary non-personal contextual information, is to be made openly available.

Why Citizen Science?

Professional researchers can measure one site, perhaps ten. Comparable long-term data requires many sites, varied environmental conditions, and people who keep measuring over longer periods. No single university can achieve that alone. It can only be achieved together.

The good news: BioComm is deliberately being developed as a low-cost measurement platform, so that distributed measurements are not limited to a few specialized labs. The knowledge needed to build and operate a node can be learned.

What we need are people with gardens, fields, woodland plots. People who are curious. Who are willing to put a small device into the ground and help us make the invisible visible.

The Long-Term Vision

We want to create a data foundation with which changes in such underground networks become visible and comparable over the long term. What this may eventually mean for research, agriculture, forest protection, or society's handling of soil ecosystems is not something we wish to prejudge.

That is no small ambition. But every measurement we take brings us a little closer.

And that is exactly why we are here.

Sources & further reading

- openmyconet.de — project website with current measurement data and information on getting involved
- Bonney, R. et al. (2014): Next Steps for Citizen Science. *Science*, 343(6178), 1436–1437.



The network is here.

We are only just learning to listen.

openmyconet.de

Citizen Science for Soil Networks

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