ISSUE 4

The Macro of Myco

Researchers are getting to the root of the problems for the world's ecosystems and unearthing new futures for myco-enriched plants.

by John Upton

Reaching the lush science campus involved heading south from Delhi, just over the state border, along the trash-strewn Faridabad Road. The alkaline fields of dust along the side of the highway are poisonous to most plants, hospitable only for patches of the most rugged and ragged of species. Cars honked, buffalos labored, and I coughed. A fence loomed along the left side, opposite a temple and a rundown snack stand. On the other side of that fence, scientists were mass-producing spores that are rescuing broken down lands just like this one.

Overcrowded cities with dense pollution take their toll on the environment. (Photo: Charles Haugen CC-BY-2.0)

The auto rickshaw was still sputtering as I stepped out. I handed the driver some rupees and walked up the driveway to the guarded gates of The Energy and Resources Institute. As I stepped through TERI's fence line, I took in the spectacle of an oasis. To my left was a gleaming green golf course. Caddies stirred, mistaking my interest for that of a golfer. A guard told me cricket ovals were off to the right, past the trees and the solar panel-covered parking lot. Ahead was a wide path that disappeared into jungle.

Somebody ought hand me a drink with a miniature umbrella.

Out of the shadows of the jungle appeared an electric buggy. Internal combustion engines are banned on the campus. The buggy ferried me quietly down the path and through the half mile of acacia trees, gardens, bamboo and rows of palm trees to Alok Adholeya's laboratory on the other side.

If green-thumbed people ever got together to vote on who had the greenest thumb, this guy might win. The microbiologist is a maestro of mycorrhizae – the name given to an ancient subterranean union between fungi and plants.

"What you see here is all reclaimed land," Adholeya said proudly, welcoming me to his research station of more than a quarter of a century.

Alok Adholeya at his research station nestled within a reclaimed oasis. (Photo: John Upton)

Mycorrhiza is often abbreviated as "myco," which is the part of the word that means fungus. Rhiza means root. Add an "e" to the end of the word and you have described a plurality of such unions.

To bring today's botanical cornucopia to TERI's campus, Adholeya began rearing plants enriched with myco-infused roots in an onsite nursery.

Migration

As plants migrated from the sea onto land nearly half a billion years ago, they needed to develop root systems to anchor into the earth, to drink its water, and to draw the nutrients from its soil. These root systems were assembled with the fusion of fungus and plant cells. The new mycorrhizal bonds between the two kingdoms of life helped each invade new territory. What makes that all the more extraordinary is the fact that fungi are more closely related to animals than they are to plants – both genetically and in the ways they lead their lives. Fungi inhale oxygen and exhale carbon dioxide, just like us. They have to eat to survive; they're no better than we are at photosynthesizing. Until an evolutionary split a billion years ago, fungi and animals were one and the same.

The temperature on the campus was cooler than the insufferable late-summer heat pounding Faridabad Road. The air in here was fresh. At least, it was fresh by India's smoggy standards. "This was barren land," Adholeya said. "This was wasteland. The government didn't know what to do with it."

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Around us, beneath the grass and under the shadows of rose bushes and bottlebrush trees, myco was invisibly working its magic.

Most of the plants that live on land have roots that are encrusted with myco, including nine out of every 10 types of crop. That's greater than the 75 percent of crops that need to be pollinated by a bee or a butterfly.

To form this inter-kingdom union, a fungus latches onto roots and unfurls microscopically thin roots of its own. These fungal roots, called mycelia, forage as much as several yards through the soil, gathering nutrients and water. Some of what they find is fed up to the plants. A fungus also holds onto some of the water, boosting the soil's moisture level as an emergency reserve in case of a dry spell. The fungus is farming. In exchange for nutrients and water, a plant passes sugars from its photosynthesizing leaves down to its roots. There, the carbohydrates meet humble fungal dietary requirements.

Artist Annabel Howland's wall painting is an interpretation of hairy carrot root cultures, which are used to grow mycorrhizal fungus. (Photo: Annabel Howland)

It's a union that humans have a wont to tear apart. We pave over mycorrhizhae. We poison it with plumes of pollution. We bulldoze forests, destroying the fungi that grew among the roots. We shred webs of underground mycelia with ploughs and pipeline projects. Many regard tilling as necessary for healthy soil, breaking it up and giving it a chance to breathe. But Mike Amaranthus, a former associate professor at Oregon State University, points out that soils were doing just fine for millions of years before the idea of till-based agriculture started to spread. "Tillage has only been around for 12,000 years; mycorrhizal fungi for 460 million years," he said. Amaranthus is one of myco's great salesmen – he has founded a thriving business based on it. "Tillage is hard on mycorrhizal fungi. The same goes for fallowing, erosion, and compaction. Tillage helps with soil aeration only temporarily – over time it destroys soil aggregation."

Then again, some soil is just naturally crap.

Adholeya doesn't blame humanity for the state of the land that blighted TERI's campus site when he joined the NGO in 1987. He took the job after completing his doctorate in mycorrhiza, at the same time that TERI was preparing to build its campus on the donated land. The rocky land here was "naturally barren," he says, used only for grazing after monsoon rains. Best Adholeya could tell, this land had been bad ever since salty seas pulled back from this part of the subcontinent. "That's the only explanation," he said, for all the salt that was in the soil.

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The naturally barren land resembled wastelands that pock parts of India and the rest of world; many of them the broken-down consequences of pollution and poor land management. The barren canvas offered the young scientist acres of seemingly useless soil to work with – the same crappy soil that crunched beneath my Blundstones at the edge of Faridabad Road. "We wanted to develop various models for wastelands," Adholeya said. "Our main objective was to try to get biomass from a wasteland. Biomass has become very important for energy, and we're an energy institute."

In contrast to the bustle of the city, life near TERI reflects a much different pace. (Photo: John Upton)

Adholeya leaned back a little in his chair at the corner of the long conference table as he recalled the history of this land. He closed his eyes, gently. Only after this routine would the microbiologist weave his tale of TERI's Gual Pahari campus.

"Millions of years ago, it would have been a sea here," he began. "The salts were making this soil highly alkaline. We used to bring water in Gypsy vans from Delhi for our nurseries because the water was bad. The water here was highly saline."

Adholeya remembered when tree saplings were drooping within a day of being planted. Inspections revealed that their roots had been devoured by termites.

"There used to be an immense number of termites, because termites love dry places and sandy soils," he said. "They were eating vegetation that came in during monsoon times – that's how the whole ecosystem was working."

The soil back then had a pH of 11 on the scale of one to 14 – extremely alkaline. There was no organic matter to speak of and any topsoil that started to accumulate during the winter would run off with the summer monsoon. Rivulets and gullies formed during heavy rain and set hard when the landscape dried.

This was no restoration project – the newly crowned doctorate aimed to breathe life into land that had never known it. Myco-enriched plants were introduced into the harsh earth, planted in a succession of species. The first plants to go in were the hardiest ones, those that were the most tolerant to salty soil. They included a fruitless variety of a tropical tree that normally produces purple berries known locally as jamun. Poplar trees also went in. By 1993, the team was planting the next wave of species – hardy acacias and bamboo. By '96, the groundwater was fresh and the land looked much as it does today, vegetated from scratch in less than a decade by embracing the natural union between fungus and plants.

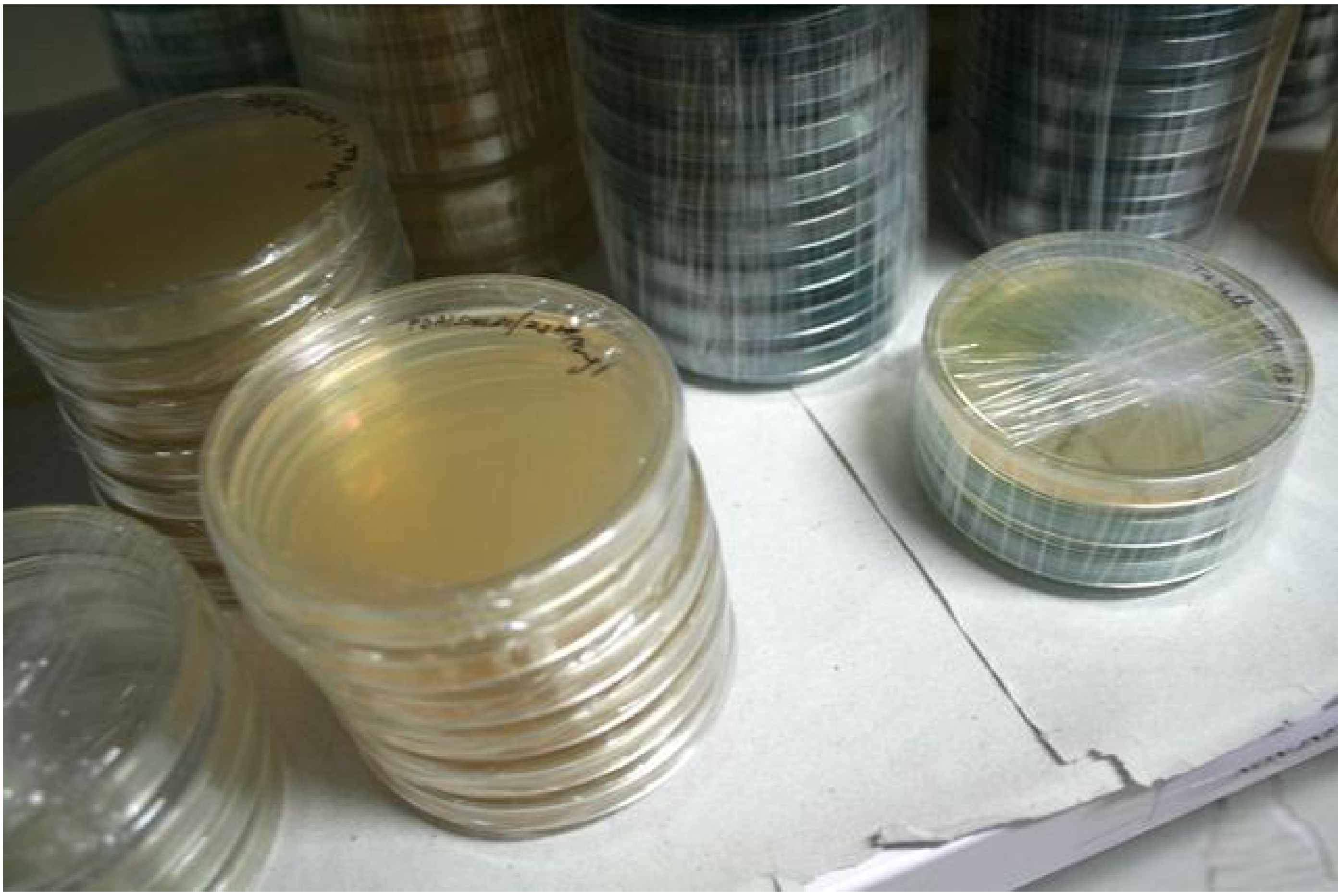
Rigging the Market

The soil beneath the TERI campus's green canopies is still yellow and sandy to the touch, but it is healthy – deceptively rich in carbon and no longer severely alkaline. That's because the myco fungi produced acids that brought the pH level below 8. The acids and enzymes reshaped nutrients in the soil, making them useful for plants. "So-called poor soils have an abundance of non-available nutrients," Adholeya said. And the called poor soils have an abundance of non-available nutrients," Adholeya said. And the soils now contain glomalin. Discovered by America's agricultural department in the 1990s, globs of glomalin are carbon-rich hunks of soil produced by myco fungi. They are used as glue to gum up soil around growing mycelia, creating passageways for nutrients and water. An experienced gardener can gauge the quality of soil by rubbing it between their fingers, judging its tilth. It is glomalin that causes soil to clump up in delightful aggregates, and it is glomalin that gives healthy soil its wonderfully tilthy quality.

Globs of glomalin, carbon rich chunks of soil, are produced by myco fungi resulting in rich, tilthy soil. (Photo: NRCS Soil Health CC-BY-2.0)

A healthy myco layer doesn't just help the soil – it helps the planet. When plants and their myco partners colonized land, they drew carbon dioxide out of the air and deposited it into the expanding soil. Carbon that used to be in the air was drawn into the Earth's crust. As much as a quarter of the carbon in the world's soil is now estimated to be in the form of glomalin. Research published in Science in March found that between 50 and 70 percent of the carbon stored in a Swedish forest was held not in the trunks and leaves, but in the soil – the so-called rhizosphere around the plants' roots. The destruction of forests and the tilling of soil is releasing carbon from glomalin back into the air, where it's contributing to global warming. Myco fungi are the only organisms capable of producing the glomalin needed to draw it back into the earth.

"Soils are just great opportunities for actually taking carbon out of the atmosphere," Amaranthus said. "It's the fastest way you can do it. It'll last in the soil for 25 to 40 years. There's a high point where you can't get any more carbon in the soil, but we're not even close to that."



On stemless roots, cultivated spores are easier to store and lighter to ship. (Photo: John Upton)

In the process of reviving the land at TERI's campus, Adholeya built up a research team that now employs some 15 scientists drawn from around the world, plus about 35 support staff. TERI's Centre for Mycorrhizal Research has identified some of the most useful strains of mycorrhizae known – and figured out how to isolate and sell them. When Adholea finished his PhD, the only way to cultivate myco was to strip it from the roots of plants. His group figured out how to cultivate spores in the laboratory by growing them on special stemless roots. Without dirt bogging down prized myco strains, they have become easier to store and lighter to ship – and it has become faster to produce the spores in vast volumes. The team's most recent breakthrough was the automation of seed coating. Until a year ago, farmers would often blend their seeds in cement mixers with commercially purchased myco spore mixtures. Now, he says, "it will be coated by the seed company." TERI exports vials of spores worth millions of dollars apiece as far away as Europe and the U.S., where companies that trade in spores, myco-infused seeds, and expertise are flourishing.

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One such company is the company co-founded in 1996 by Amaranthus – Mycorrhizal Applications. The Oregon-based company pays a licensing fee to use TERI's spore-production technology and it's preparing to use the seed-coating technology for soybeans. The company's myco products are ingredients in hundreds of products sold in hardware stores and big box outlets. It produces and sells a million pounds a year of myco spores in powder, granular, and liquid forms, ready to be applied to seeds and soils destined for fields, gardens, and polluted sites.

"We've come up with [myco] growing methods that are mechanized," Amaranthus said. "We produce product in bulk instead of in small batches and we have large processing facilities. We've continued to invest in bigger machinery, more automated approaches and the ability to concentrate the product.

"We've had 17 straight years of growth. It's a growing industry," he said.

And more growth might be in store – of a different variety. The power of myco fungus lies in its partnership with plants. The relationship is known as mutualism – each species benefits. But what if we could make a fungus more generous – turn it into a selfless worker that fetches nitrogen, phosphorous and water for plants while asking for a pittance in return?

Vrije Universiteit Amsterdam researcher Toby Kiers thinks cheap-date-tolerating fungi hold promise for the ecosystems of the future -- a world in which land recovers more quickly and produces more bountiful crops than ever before.

Toby Kiers studies the fungal economy and, ultimately, their "decision-making skills." (Photo: Seth Carnill)

Kiers is preparing to conduct a series of experiments using different strains of myco fungi. She has secured funding to watch mycelia squeeze through tiny mazes, peering at them through microscopes as they trade nutrients with plants for sugars under different conditions. The goal, she says, is to “study their decision-making skills.”

Kiers thinks of the teeming biological activity just beneath her feet as an underground economy – a natural commodities exchange desk. She plans to rig the market.

The underground economy arises because many myco fungi latch onto the roots of many plants, and many plants are connected to each fungus. That means there are lots of participants in the market to keep each other in check. Scientists can approximate the exchange rates in these rhizosphere economies, calculating how many micrograms of phosphorous, for example, a fungus must provide to a plant in exchange for a microgram of sugar. Kiers and other scientists have discovered that cheaters are penalized. A plant will withhold food from a fungus that isn’t providing nutrients at the going rate. Fungi punish cheating plants by withholding nutrients.

Kiers plans to use her experiments to help isolate and breed myco fungi strains that care little about the going exchange rates. She wants to find the sucker varieties that are willing to work the hardest for the littlest pay.

“Right now, it’s like a free-market economy,” Kiers said. “The idea, ultimately, is to change the market dynamics through selection pressures. What we want to do is have a relationship that’s much more altruistic from the fungal point of view. We want to select for the fungus that’s very good at getting nutrients and giving them to the host plants, but that doesn’t demand much sugar in return.”

Kiers plans to use traditional farming methods in her quest for selfless fungus. “It’s old school – it’s really like breeding,” she said. Selective breeding produced domesticated sheep and dogs, gave the world productive cornfields, and yielded apples that were juicier than those found in nature. Now, Kiers and TERI are adopting similar breeding approaches as they work to improve on natural myco strains. “People don’t really breed fungi, but it’s becoming more possible to do.”

Even without the promised arrival of Kiers’s do-gooder strains of futuristic fungi, myco is helping farmers and gardeners boost their harvests. Myco-loaded products that can be added to a vegetable patch or a furrow at planting time can be found in most garden and hardware stores or ordered online.

A healthy crop of Myco-loaded strawberry seedlings. (Photo: John Upton)

But for the most impressive of the mycorrhizal feats, look to once-polluted wastelands. TERI’s myco concoctions were mixed with the roots of mangrove plants to help reclaim 60 acres of land ruined by alkali-chlor sludge along the shorelines of Gujarat in the country’s west. “There are trees and grasses there that are self-sustained – they’re not watering them," Adholeya said. "The rainfall is sufficient." More recently, TERI began working with a fertilizer company in the Indian state of Andhra Pradesh that is preparing to clean up a gypsum wasteland. "We raised the plants at their nursery with local materials and our spores."

What could be possible with future generations of selfless myco? Could Iraqis farm the desert? There's no reason why not. Similar efforts are already underway in Abu Dhabi, Kuwait and Oman. What about the moon? Is that worth shooting for? NASA seems to think so. The space agency is starting to experiment with moon-based agriculture and its space gardener, Robert Bowman, said lunar farming experiments will eventually "depend on regenerative life support," including "mychorrhizae and a suite of other organisms."

That's some far-out thinking. But it's a reminder of the astronomical improvements in store for our planet as the fungal-powered underground revolution creeps forward. TERI's converted wasteland is just the beginning.

The Kiers Lab researches new ways to help lands recover quickly and ensure the future of ecosystems. (Animator: Niels Hoebers)

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Contributors

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Story Cover Photo: *Mycelia* by Laurel Fan (CC-BY-SA-2.0)