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The Underground Carbon Economy: How Fungi Trade, Hoard, and Negotiate

Environment * Climate Change * Energy

Introduction: The Invisible Engine of the Biosphere

For centuries, scientific models of the terrestrial biosphere remained overwhelmingly surface-centric. Biological surveys, conservation strategies, and climate simulations prioritized visible flora and fauna while treating the soil beneath as an inert mineral substrate passively exploited by plant roots. In the early 21st century, high-resolution imaging and molecular ecology have overturned this paradigm, revealing the subterranean environment as a dynamic, self-organizing biological marketplace.

In January 2026, this conceptual revolution received formal global recognition when evolutionary biologist Dr. Toby Kiers was awarded the Tyler Prize for Environmental Achievement.[6] Carrying a $250,000 USD award and widely regarded as the "Nobel Prize for the Environment," the honor recognizes Kiers's pioneering investigations into mycorrhizal fungi -- vast microscopic networks that link plant roots and mediate the reciprocal exchange of mineral nutrients for photosynthetically fixed carbon.[2][6] Challenging romanticized portrayals of subterranean nature as an altruistic commune, Kiers demonstrated that underground ecosystems operate as competitive economic markets governed by supply and demand, resource hoarding, price discrimination, and reciprocal sanctions.[2][3]

The significance of these mechanisms extends well beyond evolutionary theory. As humanity confronts accelerating climate change and biodiversity loss, mycorrhizal networks have been identified as a major structural carbon sink. Quantitative syntheses indicate that terrestrial plants allocate approximately 13.12 billion tons of carbon dioxide equivalents (CO_2e) annually to subterranean fungal networks -- roughly 36 percent of global fossil fuel emissions.[1] Through both biophysical imaging at Vrije Universiteit Amsterdam and global conservation mapping via the Society for the Protection of Underground Networks (SPUN), Kiers's work has positioned the microbial majority at the center of planetary climate policy.[4][6]

The Biological Marketplace: Economics Without Brains

Kiers's research program began during field expeditions in the rainforests of Panama, where she questioned how mycorrhizal mutualisms remained evolutionarily stable over hundreds of millions of years of coevolution. Standard evolutionary theory posits that natural selection favors individuals maximizing their own reproductive fitness. In an unpoliced mutualism, "cheaters" that extract resources without reciprocating should proliferate and destabilize the partnership. At the University of California, Davis, and subsequently at Vrije Universiteit Amsterdam, Kiers applied Biological Market Theory (BMT) to test whether subterranean symbioses are stabilized by economic enforcement mechanisms.[2]

In the subterranean marketplace, trade is driven by elemental complementarity. Vascular plants fix atmospheric carbon via photosynthesis into hexose sugars and fatty acids, but their coarse root architectures are inefficient at extracting immobile soil minerals. Conversely, mycorrhizal fungi lack photosynthetic machinery but deploy dense, filamentous networks of hyphae capable of penetrating microscopic soil pores to scavenge phosphorus and nitrogen. Using in vitro root organ cultures and compartmentalized split-plate experiments, Kiers and her colleagues demonstrated that fungal networks execute three distinct market strategies despite lacking a central nervous system:[2][3]

* Price Discrimination: When a single fungal mycelium links multiple host roots simultaneously, it detects differences in carbon provisioning and preferentially allocates higher fluxes of phosphorus to the host plant offering the highest carbon return.[2]

* Resource Hoarding and Spatial Arbitrage: Rather than flooding the market when soil phosphorus is locally abundant -- which would depress the carbon price paid by plants -- fungi polymerize inorganic phosphate into long-chain polyphosphate granules sequestered within their vacuoles. This biochemical banking creates artificial scarcity, allowing the mycelium to transport nutrients from rich soil patches to nutrient-poor zones where water- or mineral-stressed plants pay a higher carbon premium.[3]

* Reciprocal Sanctions: Both kingdoms actively police exchange rates. If a fungal strain fails to deliver phosphorus, the host plant restricts carbohydrate export to that specific root sector; conversely, if a plant reduces carbon allocation, the fungus diverts mineral transport toward more lucrative trading partners.[2]

This empirical framework contrasts sharply with the "Wood Wide Web" or "Mother Tree" hypothesis popularized by forest ecologist Suzanne Simard, which emphasizes cooperative resource sharing across forest canopies. While acknowledging extensive inter-plant connectivity, Kiers's market model demonstrates that subterranean networks are stabilized not by ecosystem-level altruism, but by strict bilateral conflict resolution and fitness optimization -- including extreme cases such as mycoheterotrophic orchids that parasitize fungal carbon lines entirely.[2]

Rendering the Invisible Visible: Biophysics and Quantum Dots

Historically, the physical opacity of soil prevented direct observation of intact mycelial trade; physical excavation severs hyphal architecture and halts cytoplasmic streaming. To overcome this barrier, Kiers's laboratory collaborated with the Amsterdam Biophysics Institute (AMOLF) to engineer a high-throughput robotic imaging platform coupled with nanoscale fluorescent tracers.[3][5]

The robotic microscopy apparatus tracks living fungal networks continuously across weeks of growth, resolving dynamic bidirectional cytoplasmic streaming, branching topology, and oscillatory flow reversals in real time.[5] To quantify nutrient transactions directly, the team conjugated inorganic rock phosphate (apatite) with fluorescent semiconductor nanocrystals -- quantum dots -- that emit bright, photostable signals under specific excitation wavelengths.[3][5] By introducing differently colored quantum-dot-tagged phosphorus into spatially separated

compartments connected to carbon-rich versus carbon-poor host roots, researchers tracked individual nutrient packets using confocal microscopy and raster image correlation spectroscopy. The tracking confirmed that fungi actively strip phosphorus from nutrient-rich zones and route it past poor hosts to invest in high-carbon-paying partners, providing the first direct visual proof of inequality management in non-neural biological networks.[3][5]

The Global Mycelial Carbon Sink

While behavioral trade occurs at the micron scale, its aggregate biogeochemical footprint is planetary. In a landmark synthesis published in Current Biology (Hawkins et al., 2023), Kiers and an international consortium analyzed nearly 200 datasets to quantify the fraction of net primary productivity exported by terrestrial vegetation to mycorrhizal networks within the global carbon cycle.[1]

The study calculated that global plant communities transfer approximately 13.12 gigatons (Gt) of CO2e per year to underground fungal partners -- exceeding the annual fossil fuel emissions of China (~12.5 Gt) and nearly tripling those of the United States (~4.7 Gt).[1] This flux is partitioned across three primary guilds: ectomycorrhizal (EcM) fungi associated with temperate and boreal forest trees (~9.07 Gt CO2e/year), arbuscular mycorrhizal (AM) fungi dominating grasslands, tropical forests, and agricultural crops (~3.93 Gt CO2e/year), and ericoid mycorrhizal (ErM) fungi in high-latitude heathlands and tundra (~0.12 Gt CO2e/year).[1]

Rather than immediately respiring back to the atmosphere, a substantial share of this carbon constructs structural mycelial biomass rich in recalcitrant chitin, melanin, and beta-glucans. Upon hyphal senescence, this fungal necromass -- reinforced by glycoproteins such as glomalin that bind mineral particles into stable microaggregates -- shields organic carbon from oxidative degradation by soil bacteria for decades to centuries.[1]

| Carbon Sink / Source | | Estimated Annual Flux (Gt CO2e) | | Ecological Context & Guild Partitioning |

| Global Fossil Fuel Emissions (2021) | | ~36.30 | | Total anthropogenic combustion and industrial baseline |

| Total Allocation to Mycorrhizal Fungi | | ~13.12 | | ~36% of global fossil fuel emissions; major terrestrial sink[1] |

| China Annual Emissions (2021) | | ~12.47 | | Largest single-nation anthropogenic emitter |

| Ectomycorrhizal (EcM) Fungi | | ~9.07 | | Temperate and boreal woody forest ecosystems[1] |

| US Annual Emissions (2021) | | ~4.70 | | Second-largest national anthropogenic emitter |

| Arbuscular Mycorrhizal (AM) Fungi | | ~3.93 | | Grasslands, tropical forests, and global croplands[1] |

| Ericoid Mycorrhizal (ErM) Fungi | | ~0.12 | | Boreal heathlands and peat-rich tundra soils[1] |

SPUN, the Underground Atlas, and Legal Advocacy

Despite sequestering over a third of fossil fuel emissions equivalents, subterranean ecosystems remain virtually absent from international conservation frameworks. Spatial overlap analyses conducted by the Society for the Protection of Underground Networks (SPUN) -- co-founded by Kiers -- revealed that roughly 90 percent of global fungal biodiversity hotspots lie outside existing protected areas, with only 5.1 percent of AM fungal hotspots and 13.9 percent of EcM hotspots enjoying formal protection.[4] Because subterranean fungal richness frequently diverges from above-ground plant diversity -- peaking in regions like high-latitude boreal forests or semi-arid steppes -- surface-driven conservation leaves critical soil carbon engines exposed to industrial tillage, deforestation, and coastal erosion.[4]

To close this protection gap, SPUN developed the Underground Atlas, the first high-resolution global map of mycorrhizal biodiversity.[4] By aggregating over 2.8 billion fungal DNA sequences from 25,000 georeferenced soil samples across 130 countries, SPUN trained ensemble machine-learning models against climatic, edaphic, and topographic covariates to map fungal species richness and endemism at a 1-square-kilometer resolution worldwide. The Atlas highlighted urgent conservation priorities, including the AM-rich grasslands of the Kazakh Steppe, endemic ectomycorrhizal communities in northern Mexican conifer forests, and the rapidly eroding coastal scrublands of Ghana -- where sea-level rise is claiming two meters of coastline annually, necessitating emergency "salvage biology" sampling.[4]

| Underground Atlas Parameter | | Technical Specification | | Conservation Application |

| Genetic Input Dataset | | 2.8 billion fungal DNA sequences | | Comprehensive molecular inventory of subterranean taxa[4] |

| Field Ground-Truthing | | 25,000 soil samples across 130 countries | | Empirical calibration across diverse global ecoregions[4] |

| Spatial Resolution | | 1 km (30 arc-seconds) | | Parcel-level targeting for land-use planning and reserves[4] |

| Core Output Metrics | | Richness, Endemism, Model Uncertainty | | Prioritizing unprotected hotspots and guiding sampling expeditions[4] |

Coinciding with the 2026 Tyler Prize announcement, SPUN partnered with New York University Law's "More-Than-Human Life" (MOTH) project to launch the Underground Advocates initiative.[6] This program trains researchers and Indigenous and local communities to integrate Underground Atlas datasets into environmental impact assessments, national biodiversity strategies, and "Rights of Nature" legal frameworks that accord formal protection to "funga" alongside flora and fauna.[4][6]

Conclusion: Integrating Soil Markets into Climate Policy

Dr. Toby Kiers's 2026 Tyler Prize marks a decisive turning point in environmental science: the recognition that terrestrial ecosystem resilience and climate policy depend directly on the microscopic commerce beneath our feet.[6] By uniting nanoscale biophysics, evolutionary market theory, and planetary-scale machine learning, Kiers has demonstrated that mycorrhizal networks are neither passive

conduits nor socialist communes, but ancient, self-regulating economies that lock billions of tons of carbon into the Earth's crust.[1][2][3] Protecting the genetic diversity of these subterranean traders -- and harnessing high-efficiency fungal strains to restore degraded agricultural soils -- will be indispensable to stabilizing the biosphere in the decades ahead.[4]

Updates... (Nov 21, 2026): Replaced the root organization homepage link with the primary Nature study mapping global mycorrhizal hotspots (Van Nuland et al. 2025, DOI: 10.1038/s41586-025-09277-4); added specific publication dates verified against CrossRef and VU Amsterdam records across all six references; and standardized reference list markup.

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