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A key to mitigate climate change hides beneath our feet in soil fungi

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Abstract

Soils act as vast reservoirs for the Earth's carbon, and even a minor alteration in the soil's carbon content can have a profound effect on the stability of our atmosphere. Scientists have recently recognized the substantial carbon storage capacity within soil fungal networks, particularly the mycorrhizal mycelial network. It's estimated that up to 36% of annual global carbon emissions are stored within this network.

Although there's still much to uncover about mycorrhizal fungi, their role in carbon sequestration within the soil is undeniable. A renewed focus on managing soil carbon levels with the aid of mycorrhizal fungi is both logical and timely. Climate-smart soil management practices should aim to preserve and enhance this network's integrity and productivity. This is especially vital in agricultural settings, where there exists immense potential to foster a mycelium network across vast expanses of land. This paper provides a checklist of nine actionable steps individuals can take to enhance the transfer of carbon dioxide from the atmosphere to the soil.

Instead of adhering to a zero-sum perspective on agriculture—where gains in one area come at the expense of another—a more holistic approach is imperative. We need to cultivate a symbiotic relationship with soil and agriculture that not only meets our food requirements but also bolsters soil fertility, enhances food quality, and sequesters carbon in the earth. This leads to the question: Can agriculture and mycorrhizal fungi collaboratively combat climate change? Scientists are increasingly recognizing the substantial carbon flows within subterranean fungi and their potential in climate change mitigation. The solution to climate change might very well be right beneath our feet, concealed within these transformative fungi.

Introduction

There is so much bad news about our planet in the media these days that we often feel overwhelmed and powerless. And for good reason, the carbon dioxide content of our atmosphere has surged by 50% since the start of the Industrial age, resulting in melting glaciers, and shifts in plants and animal environments. The predicted consequences of global climate change, such as the loss of sea ice, sea level rise, and more prolonged, severe heat waves, are now unfolding. The repercussions are already evident in health issues arising from air pollution, disease, extreme weather events, wildfires, droughts, forced displacement, and strains on food production. So, what can we do about it?

We helplessly scroll down the page to the next story.

But before you turn the page on this article, I want to propose that there is a small, simple, and cost-effective solution right beneath your feet. Something that nature has been working on for hundreds of millions of years. A solution in the form of small, overlooked filaments in the soil called mycorrhizal fungi. Myco what? No need to panic. This article will explain what these organisms are, and do, in simple terms.

First a little discussion about where we are climatically and carbon-wise now. Scientists have long recognized a direct correlation between atmospheric carbon dioxide and rising global temperatures, known as the greenhouse effect. One proposed method to curb atmospheric carbon is to put it in the ground and increase soil carbon. Soils harbor about 75% of the carbon pool on land, three times more than that stored in living plants and animals.

Figure 1. Sequestering atmospheric carbon dioxide into soil and mycorrhizal fungi is an effective change to our approach to the climate crises.

Substantial amounts of soil carbon have already been released into the atmosphere through historical and contemporary agricultural practices, leading to an increase in atmospheric carbon dioxide levels. In the last 50 years atmospheric carbon dioxide levels have risen from 320 ppm to 415 ppm [1]. Usually, these kinds of changes in the atmosphere occur over geologic time scales. The dawn of agriculture 12,000 years ago, involving the clearing of natural ecosystems and soil plowing, released a significant amount of carbon dioxide into the atmosphere. This historical footprint is traceable in glacial ice [2]. The ongoing release of soil carbon into the atmosphere as carbon dioxide is produced by certain conventional agricultural methods and the degradation of natural ecosystems.

What to do about it? Soils play a crucial role in maintaining a balanced global carbon cycle, with recent research highlighting the significant role of tiny soil fungal filaments, specifically mycorrhizal fungi, in sequestering carbon. The fungal filaments are small but their effect on our climate is large. Recognizing their potential impact on our survival in the face of catastrophic climate change is imperative.

The public, however, remains largely uninformed about the importance of mycorrhizal fungi in moderating the Earth's climate. This paper aims to bridge the gap between expanding scientific knowledge and public awareness, shedding light on the benefits of mycorrhizal fungi and their role in combating climate change. Additionally, it offers specific recommendations for individuals to leverage their resources and activities in utilizing these beneficial fungi to store carbon, providing hope and actionable steps amid the daunting climate challenges we face.

What is Carbon Sequestration?

Carbon sequestration involves the prolonged storage of carbon in oceans, soils, vegetation, and geological formations, with most of the land-based carbon stored in soils. Carbon serves as the primary building block for all life, existing in diverse forms, predominantly as plant and fungal biomass, soil organic matter, and the gas carbon dioxide (CO^2) found both in the atmosphere and dissolved in seawater.

In the intricate process of photosynthesis, plants absorb carbon, releasing a portion of it back into the atmosphere through respiration. However, a substantial amount of carbon is transported beneath the soil surface. The storage reservoir within the soil is known as soil organic matter and living soil biomass. It is an intricate mixture of carbon compounds derived from decomposing plant and animal tissue, carbon linked with soil minerals, and carbon integrated into roots and their associated soil microbes. Recent discoveries highlight the significance of the soil microbe component, particularly the filaments of mycorrhizal fungi, as vast pools of carbon.

Figure 2. Healthy ecosystems absorb carbon dioxide and store vast amounts of carbon into soil. Degraded ecosystems do not.

Myco what? What are mycorrhizal fungi?

Over 400 million years ago, a pivotal agreement was forged between plants and mycorrhizal fungi, marking one of the most successful partnerships in evolutionary history—a pact that often goes unnoticed and underappreciated by humans. In this symbiotic relationship, plants provide mycorrhizal fungal filaments (commonly known as mycelium) with sugar generated from sunlight through photosynthesis. In return, the fungi extend profusely into soil to supply plants with essential nutrients and water crucial for plant productivity.

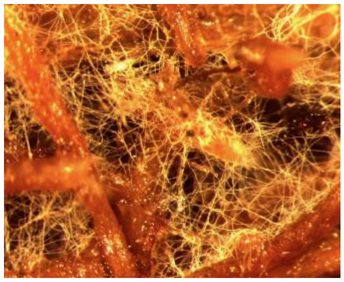


Figure 3. Miles of mycorrhizal fungal filaments can be present in a tablespoon of healthy soil.

This partnership is widespread, involving nearly 90% of all plants in their natural habitats. While the significance of mycorrhizal fungi in facilitating plant nutrition and water uptake is well-established, their role in the global-scale transportation and storage of carbon into soil systems is just now being appreciated. Scientists have long suspected that substantial amounts of carbon flow through these underground fungi. However, they didn't realize how much carbon was in the system until now. The extent of this underground network is staggering; a mere spoonful of healthy soil may harbor miles of fungal filaments and the carbon within.

Figure 4. Mycorrhizal fungal filaments are fed carbon from the plant and radiate from a mycorrhizal root (scanning electron micrograph).

Mycorrhizal fungi are enormous carbon sinks.

What potential could mycorrhizal fungi have to mitigate the catastrophic effects of climate change? According to a recently published article in the journal , *Current Biology* [3], researchers examined 194 data sets from 61 peer-reviewed papers and four unpublished studies to determine how much carbon plants allocate to fungi. On average more than 13 billion metric tons of CO^2 is passed from plants to mycorrhizal fungi each year. To give some perspective on the significance 13 billion metric tons of $CO^{2,}$ the total planetary emission in 2022 were 37.12 billion metric tons and 37.55 billion metric tons in 2023. The 13 billion metric tons represented in allocation to mycorrhizal fungal filaments is equivalent to around 36% of all annual global fossil fuel emissions. That's comparable to the amount of carbon than China puts in the atmosphere each year!

The clock is ticking. Global emissions of CO^2 have increased 60 percent since 1990. China is the world's largest emitter, followed by the United States.   China's CO^2 emissions have grown 400 percent since 1990. Even with large investments in CO^2 reduction strategies, U.S. emissions have only decreased 2.6 percent. Mounting evidence indicates that something must be done, however, enormous carbon sink represented by microscopic fungi has been largely ignored in climate change research and modeling. Understandably, much focus has been placed on protecting and restoring forests as a natural way to mitigate climate change. But little attention has been paid to the fate of the vast amounts of carbon dioxide that are moved from the atmosphere during photosynthesis by plants other than trees and sent belowground to mycorrhizal fungi.   Most agricultural crop species form a mycorrhizal relationship with mycorrhizal fungi but have been eliminated or greatly reduced by certain agricultural practices. Reestablishing this relationship on billions of agricultural acres has huge potential in terms of sequestering carbon.

Figure 5. Photo Rodale Institute Long-term farming systems trial: the soils on the right were grown with regenerative organic methods and mycorrhizal fungi: on the left conventional practices. The darker soil (right) has 20 percent more carbon after 20 years in the side-by-side trial.

Increasing the carbon content of soil can happen rapidly. The Rodale Institute's farming systems trial is the longest side by side comparison of regenerative organic and intensive chemical farming methods [4]. The soil managed with regenerative organic methods had cover crops, abundant mycorrhizal populations, and increased carbon levels at a rate of 1000 lbs. per acre per year for 20 years**.** The work of Rodale research collaborator, Dr. David Douds of the USDA Agricultural Research Service, suggests that healthy mycorrhizal fungi populations in regenerative organic systems increases crop productivity while sequestering carbon [5,6]**.** Without question, soils farmed with regenerative organic systems have greater populations of mycorrhizal fungi. Less chemicals, organic fertility inputs and overwintering cover crops supply energy to fuel populations of mycorrhizal fungi in the regenerative organic system, in contrast to the conventional systems, which generally have a significantly greater fallow period and use more chemical fertilizers and pesticides.

Organic approaches to soil management are not "pie-in-the-sky approaches" but are proven ways to increase the carbon content of soil [4]. Many of today's regenerative organic farming practices combine methods that increase carbon content in the soil. Instead of relying on synthetic pesticides and fertilizers, regenerative farming entails soil carbon-building practices such as growing legumes and other cover crops, diversified crop rotations, inoculation with mycorrhizal fungi, and incorporation of animal manures and compost.

Healthy soils are a carbon sponge. Governments are beginning to recognize the importance of adding carbon to soil. The French government has proposed an initiative to add .4% carbon (4 parts per 1000) to its soils each year [7]. Does this seem insignificant? Hardly. If all the countries of the world add a .4% carbon to their soils, it would store up to 75% of the global annual carbon emissions [8}. There are an estimated 4.6 billion acres of farmland globally considered "agricultural areas" by the FAO (approximately 35% of the planet). What we need is more photosynthesis and practices that encourage life and carbon sequestration in agricultural soils.

Let's rethink how we treat the soil

It's time to quit treating soil like dirt. Conventional farmers are finding ways to incorporate regenerative methods into farming practices. For example, many farmers have used reduced tillage, green manures and mycorrhizal inoculation to turn lifeless soil into a carbon sink. Mycorrhizal fungi are recognized in the scientific community as key components in global ecosystem functioning and are a “canary in the coal mine” indicator for how we are treating the soil. Recently, they are drawing attention for special significance in terms of ameliorating the effects of global warming [9]. Studies are determining what conditions decrease or increase mycorrhizal activity in soils.

Highly disruptive practices such as land clearing, erosion, compaction, high levels of chemical fertilizers and pesticides and organic matter removal can turn living soil into lifeless dirt [9]. When we damage soils, carbon goes back into the atmosphere. Growing in healthy soil, plants take more carbon dioxide out the air and allocate and store carbon into mycorrhizal biomass. This is precisely what happens in natural ecosystems all over the world. Unfortunately, the health of these natural ecosystems has deteriorated in the last century, adversely affecting the plants and the living soil responsible for fixing and storing carbon into the soil.

Figure 6. A tractor tills the soil before planting. Tilling soils releases vast amounts of soil carbon into the atmosphere and destroys mycorrhizal fungal populations that sequester carbon.

Thankfully, we know which agricultural methods and impacts have detrimental effects on mycorrhizal fungal activity in the [5,10]. Extensive laboratory and field testing has demonstrated that most intensively managed agricultural lands often lack sufficient soil structure and populations of mycorrhizal fungi [5]. The absence of the binding power of mycorrhizal filaments not only leads to the deterioration of soil structure but also compromises a substantial number of fungi protected within soil aggregates [11]. These fungi may not only contribute to the soil carbon content but also play a critical role in the health and function of the entire soil ecosystem [12,13].

One agricultural practice, tilling, is particularly detrimental. Tilling before planting, often executed with a plow, or disk is known for its efficacy in eliminating existing vegetation like sod and weeds by disturbing and inverting the soil. Tillage, however, has been identified as particularly disruptive to beneficial mycorrhizal fungal populations [14,15,16]. Additionally, tilling can also expose soils to issues such as loss of soil structure, compaction, and erosion. Research findings highlight the potential benefits of no-till farming—mitigating the adverse effects on mycorrhizal fungi, soil structure and erosion associated with traditional tilling methods [17]. No-till farming practices have shown promise in increasing mycorrhizal fungal populations compared to conventional tillage methods [18].

The simple decision to eat healthy food, from healthy soils can help heal the planet. It’s a win/win/win. Adding carbon and increasing mycorrhizal fungi activity in soil increases productivity and can improve food quality [19]. These findings underscore the potential benefits of adopting more regenerative agricultural practices that support mycorrhizal fungi, not only for the enhancement of food quality but also for carbon additions to the soil and the overall health and resilience of soil ecosystems.

More Research is Needed

Recent research summary indicates that mycorrhizal fungi hold the CO^2 equivalent of a third of annual global fossil fuel emissions. More specific research is needed. Despite mycorrhizal fungi being stationed at a key entry point or carbon into soil food webs, we still lack a robust quantitative and mechanistic understanding of the contribution of mycorrhizal associations to the global carbon cycle across various ecosystems and practices.

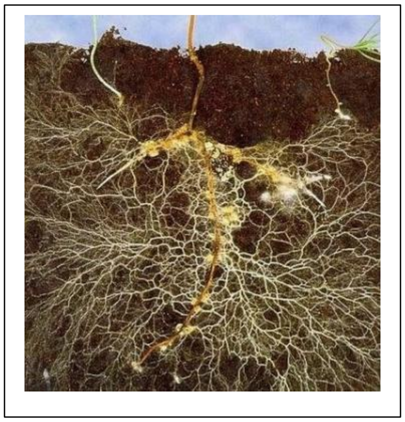


Figure 7. Only the external mycelium of mycorrhizal fungi was quantified in the *Current Biology* study.

The conclusion that more than 13 billion metric tons of CO^2 are passed from plants to mycorrhizal fungi each year may be an underestimate, and the actual figure could be even larger. The *Current Biology* study [3] used a conservative estimation by only quantifying carbon allocation to mycorrhizal fungal mycelium outside of the roots. The carbon pool of mycelium inside and on the surface of plant roots was not included study and could significantly magnify the annual 13 billion metric ton value.

We know that some of the plant's non-biomass carbon is used by mycorrhizal fungi to build mycelial networks (figure 7), but we need more information how that allocation differs between grassland, forest, and agricultural systems. More data are also needed regarding how management practices in these plant systems affect the level of carbon allocation, how rapidly this carbon degrades in the soil, and the variation by plant growth stage.

Figure 8: Arbuscular mycorrhiza. The blue colored tissues are mycorrhizal fungal structures inside the root were not included in estimates of carbon sequestration in the *Current Biology* study.

While mycorrhizal fungi are an important route for plant carbon to enter the soil, losses will also occur via fungal respiration and decomposition. Studies are needed to account for all carbon fluxes (inputs and outputs) and pools (and their decomposition rate) associated with mycorrhizal fungi and their colonized roots.

The 13 billion GT annual carbon passed to mycorrhizal fungi in the *Current Biology* paper also does not include sporocarps (mushroom fruiting bodies) , fungal exudates, and fungus inside the roots, which can vary and be significant depending upon the type of mycorrhizal fungi. For example, arbuscular mycorrhizal fungi, (figure 8) which predominate on non-forest and agricultural plant species, can have four times the fungal biomass inside the roots compared to external mycelium in the soil. [20]. Also, ectomycorrhizal fungi that predominate in northern temperate forests allocate substantial carbon to abundant fungal fruiting's of mushrooms, truffles, and puffballs [21].

Methodological limitations mean that the 13 billion GT allocation to mycorrhizal fungal mycelium may over- or underestimate the total sum of carbon that moves from plants into soils via mycorrhizal pathways. Regardless, this *Current Biology* study review of nearly 200 data sets confirms the significant contribution made by mycorrhizal associations to global carbon fluxes and should motivate the inclusion of mycorrhizal fungi within global climate and carbon cycling models, and within conservation policy and practice [22].

What Can You Do?

You can do your part to remove carbon dioxide from the atmosphere. Storing carbon in mycorrhizal fungi and soil not only helps mitigate the effects of climate change but also enhances food and soil quality and productivity. Increasing the amount of carbon stored in soils contributes to improvements in soil structure, nutrient uptake, water quality, reduced nutrient loss, minimized soil erosion, enhanced water conservation, and increased crop yields. Here are successful management techniques that foster the most prolific accumulation of mycorrhizal activity and carbon biomass, creating a net carbon sink in soils:

Agricultural and Gardening Practices:

- If you are producing food, adopt minimum or no-tillage agricultural and gardening practices to minimize adverse effects on mycorrhizal fungal activity and biomass (Figure 9). Tillage and rototilling mix oxygen with stored soil carbon, converting it to carbon dioxide. Tillage also physically destroys the mycorrhizal mycelial network and the soil structure that protects it.

Food Choices:

- When buying food, prioritize products grown with regenerative organic methods. Organic food production methods use fewer chemical fertilizers and pesticides, that can have an adverse impact of mycorrhizal fungi.

Green Cover:

- Periods of fallow (no living vegetation) reduce carbon accumulation in soil and mycorrhizal activity. Green cover enhances mycorrhizal activity and biomass by providing the carbon mycorrhizal fungi need to stay alive and function. Consider implementing cover crops, such as legumes and small grains, between periods of food production that would otherwise be fallow. (Figure 10).

Mycorrhizal Inoculants:

- Use mycorrhizal inoculants when planting highly disturbed areas or fallowed soils to reestablish mycorrhizal populations. (Figure 11).

Reduced Chemical Fertilizer Use:

- Reduce landscape and garden use of chemical fertilizers, especially those with high or quick-release levels of nitrogen and phosphorus that discourage mycorrhizal activity.

Organic Inputs:

- Incorporate organic inputs such as mulch and compost to encourage mycorrhizal activity and increase soil carbon levels.

Plant Perennials:

- Choose to plant perennials, as they provide energy for mycorrhizal populations and activity year-round.

Erosion Prevention:

- Take measures to prevent erosion, as topsoil is where most mycorrhizal populations are found and has the highest levels of soil carbon.

Support Conservation and Restoration Efforts:

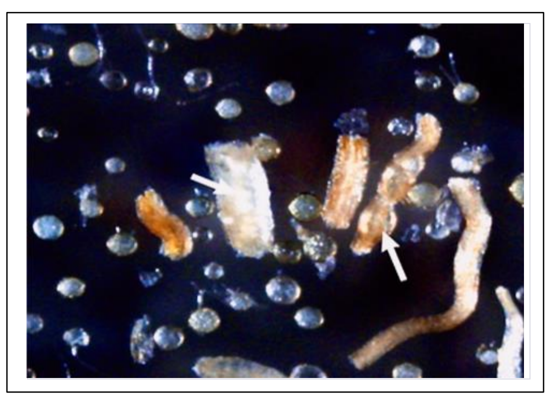
- Support conservation efforts that preserve native vegetative and the mycorrhizal communities that reside in the soil. Support restoration efforts that reverse soil degradation and restore vegetative and mycorrhizal communities.

By incorporating these practices into your agricultural and gardening approaches, food choices, and overall land management, you actively contribute to the preservation and enhancement of mycorrhizal activity and soil carbon, fostering a healthier environment and mitigating climate change effects.

Figure 9. No till or minimum till methods keep mycorrhizal mycelial networks healthy.

Figure 10. Cover crops feed and invigorate populations of mycorrhizal fungi and carbon inputs into soils.

Figure 11. Mycorrhizal spores and colonized root fragments are the active ingredients in mycorrhizal products for reestablishing mycorrhizal populations.



Conclusions

Soils serve as tremendous storehouses of the Earth's carbon, and even a small change in the percent carbon in the soil can significantly impact the maintenance of the Earth's atmosphere. Scientists have recently come to appreciate the substantial carbon presence in fungal filaments, specifically the mycorrhizal network. Up to 36% of the annual global carbon emissions are estimated to be stored in the mycorrhizal mycelial network.

Understanding the role of mycorrhizal fungi is essential for addressing increasing carbon dioxide levels in the atmosphere. Nearly 90% of all land plants are part of this mycorrhizal arrangement, and these fungi serve as primary mechanisms for interfacing the atmosphere and soil. Scientists are now realizing the significant levels of carbon flowing through underground fungi.

While much remains to be learned about mycorrhizal fungi, their effectiveness in sequestering carbon in the soil cannot be overlooked. A fresh look at managing the carbon level in soils with mycorrhizal fungi makes sense, and climate-smart soil management practices must prioritize minimizing degradation of this network while maximizing its productivity. This is particularly crucial in agricultural systems, where there is significant potential for generating a mycelium network on billions of acres.

Rather than being trapped in a zero-sum view of agriculture where one side wins and the other loses, a better way is needed. We must manage our relationship with soil and agriculture to produce the food we need while simultaneously increasing soil fertility, food quality and incorporating carbon into the ground. The question arises: Can agriculture and mycorrhizal fungi work together to mitigate climate change? The solution lies right beneath our feet, hidden in these fungal game changers.

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