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WHAT IF SOIL MICROBES MATTERED?

OUR HEALTH DEPENDS ON THEM

Leo Horrigan

ABOUT THE AUTHOR

Leo Horrigan is a food system correspondent for the Johns Hopkins Center for a Livable Future. Since 1998 he has been writing extensively on food system topics, including how to make farming more sustainable and healthy food more accessible. He also catalyzed a high school food system curriculum called FoodSpan—available for free online —and three documentary films that accompany the curriculum. Like this book, his most recent film (*Growing Solutions*, 2020) focuses on solutions to farming challenges. This book is also a sequel, of sorts, to *What If CAFOs Were History* (2023).

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PREFACE

From its inception in 1996, the Johns Hopkins Center for a Livable Future (CLF) has concerned itself with the nexus of agriculture, public health, and the environment. I'm interested in all three, so was drawn like a magnet to CLF's work.

The Center has evolved into what I would call (unofficially) a "Center for Sustainable Food Systems" —a natural evolution since food systems are a place where the above trifecta of topics resides. But food systems are vast and complex; you can't study all facets of them all at once. In previous years, much of my focus had been on critiquing the industrial agriculture system that predominates in the so-called developed world. My hunger for alternatives led me inexorably toward a study of regenerative agriculture, which might also be called biological agriculture.

Between 2010 and 2020, I made three documentary films to accompany CLF's high school curriculum about the food system, called FoodSpan. Two of those films are farming-focused, the most recent being *Growing Solutions* (2020). In the course of making that film, I interviewed pioneering soil ecologist Elaine Ingham and spent a day on her research farm in Northern California. Something she said during that interview stuck in my head: "If you want to sequester more carbon, grow more fungi," she exhorted us all.

This led me to take a course with Dr. Ingham's Soil Food Web School. A whole world was opened up to me there, one where soil microbes do a lot of unsung work that has more profound implications than anyone would imagine if they hadn't explored this world. I have come to sincerely believe that we as humans need a greater appreciation for what these microbes do. Studying them will likely cause many people to more humbly consider how humans fit into the grand scheme of things.

I am not an expert on soil ecology. But I am also no longer a neophyte in this area. My fond wish is that I've learned enough to introduce this subject in a way that will inspire you to further study up on it, and zoom past me in terms of your expertise. That, alone, would more than justify the time I've spent writing this "Little Book of Soil" and the time you were kind enough to spend reading it.

INTRODUCTION

> *"Soil health is the foundation of civilization and integral to life on the Earth."*
>
> **—National Academies of Sciences, Engineering, and Medicine (2017)[1]**

The system of agriculture that has predominated in the United States since World War II has mostly ignored soil biology. A healthy soil must contain a thriving community of organisms — without these living things, you only have dirt.[2]

Since about the middle of the 20th century, our increasingly industrialized agriculture has degraded the life in the soil, while not paying much attention to its effects on the soil's inhabitants and their ecosystem. You could say we are living in the Chemical Age of Agriculture, during which people have sought chemical solutions to farming challenges such as weeds, insect pests, plant diseases, and insufficient fertility.

Here in the 2020s, though, the stars might begin to align such that we could see a transition to a Biological Age of Agriculture that could eventually supplant our mainstream, chemical farming model. A biological style of farming puts a laser focus on what is happening with the ecology of the soil—a mostly microscopic universe that is essential to plant health. Biological farming also acknowledges that there are natural processes that supply plants with adequate nutrition, with defense against pests and diseases, and with soil habitat that facilitates root growth and nutrient exchange.

Industrial agriculture methods undermine most of these natural dynamics, but since some of our chemical interventions achieve short-term success, they give the impression that they are a true solution to farming dilemmas. However, after decades of use, those chemical interventions have:

- Put farmers on a chemical treadmill that has no end game, while more and more insect[3] and weed species[4] develop resistance to chemical controls. These methods also expose people to harmful chemicals in the form of pesticide drift in farm country and pesticide residues in our food.

- Reduced the nutrient content of our foods, as concentrations of minerals, vitamins and beneficial phytochemicals in fruits and vegetables have steadily declined for decades. In part, this is happening because so many of our mainstream farming methods (tillage, pesticides, monocultures, and synthetic fertilizers) disrupt the symbiosis between plants and soil microbes that helps plants acquire nutrients—most of which are essential for both the plant and whoever eats those plants, whether they be humans or farm animals.[5,6,7,8]
- Made farming into a net source of carbon in the atmosphere, and degraded farmland in ways that make it more vulnerable to the extreme weather events, such as droughts or floods, that are becoming more common.[9]
- Put farmers in a squeeze between the high cost of chemical inputs (pesticides and synthetic fertilizers) and the low prices they receive for their outputs. This economic imbalance has pushed many farmers out of business entirely and has had negative effects on rural economies and rural health.[10,11,12]

Because of this dubious track record, it is appropriate to seek alternative farming models that do not come with so much baggage—and can also repair the damage done by the chemical approach. Fortunately, some farmers are discovering the numerous benefits of shifting to a biological approach to solving problems and achieving success in farming. Some call this model regenerative farming because it starts with regenerating the biology in the soil. When the soil's biological community is thriving, organisms perform numerous "services" that are critical to plants. These include:[13]

1. Building soil structure
2. Making nutrients available to plants when they need them, and at the required rates
3. Retaining nutrients for future use ("the pantry")
4. Suppressing diseases and pests
5. Suppressing weeds
6. Decomposing toxins
7. Accumulating carbon

All these microbial benefits have implications for human health, as our future food security depends upon nurturing the symbiotic plant/microbe relationships that have been refined over millennia. Plants depend on microorganisms to acquire almost all of the nutrients they require, and if plants cannot acquire them because of a damaged or broken symbiosis (aka, dysbiosis), those nutrients will not show up in the human diet, either.[14] Stretching out the status quo of chemical farming means continuing to damage these critical relationships, degrading the natural resource base required for successful farming, and reducing our long-term agricultural yields and, thus, our food security.[15]

To better understand the importance of the soil food web and the promise of the regenerative farming model, let's go into some depth about each of the benefits listed above. Then, we will lay out the stark contrast between chemical agriculture and biological agriculture, in terms of impacts on the soil ecosystem, as well as further explore the implications of a healthy soil ecology (and an unhealthy one) for public health.

THE PORE HOUSE: MICROBES BUILD THEMSELVES A HOME

> *"Since food quality is of great concern to us all, the soil must be of great concern to us all, since soil health directly controls plant health … If human health concerns us, we must learn about soil life."*
>
> **—Elaine Ingham, soil ecologist[16]**

Soil structure has real implications for humans, plants and the planet. It is an underappreciated ally in our efforts to adapt to extreme weather events that have become our new normal.

Bacteria and fungi combine to do most of the work of building soil structure. Bacteria produce strong glues[17] that allow them to attach to minerals and organic matter in soil (mostly decaying plant material). This organic matter provides both a hiding place for bacteria and a food source. By gluing soil particles in this way, bacteria create microaggregates, so more pore spaces are formed, and thus there are more places for water, oxygen, and roots to penetrate.

In turn, the fungi use their long strands called hyphae to corral these microaggregates into macroaggregates, which are large enough for us to see without a microscope. This creates even more aeration in the soil. The fungi also produce a glue known as glomalin—which went undiscovered until 1996 but is now known to play a role in binding organic matter to sand, silt, and clay.[18,19,20]

Well-structured soil with plenty of organic matter can soak up water; conversely, porous soil structure also makes it easier for excess water to infiltrate into deeper layers and replenish groundwater. All this means that in wet weather the soil will not get waterlogged and then be vulnerable to erosion; and in arid conditions the soil takes longer to dry out because it contains a reserve of stored water. You can think of good soil structure as nature's stormwater management system, as healthy soil's sponge-like quality makes it more resilient in the face of weather extremes.

When fungi flourish in soil, they can help plants access water from deeper in the soil profile, since some fungi behave like an extension of the plant's root system. Fungal hyphae are thinner than plant root hairs, so they can access water in tighter spaces.

When oxygen diffuses through well-structured soil, that confers a competitive advantage upon plants and many of their oxygen-loving partner organisms, such as mycorrhizal fungi. Roots can go deeper in a well-structured soil where compaction is minimal and pore spaces plentiful. This leads to healthier plants because they have greater access to soil nutrients and water.

JUST-IN-TIME DELIVERY: SOIL MICROBES AND NUTRIENTS

It was once thought that most soils required external nutrient inputs to grow plants—especially nitrogen, phosphorus, potassium, and sulfur. Now, there is a greater understanding that infertile soils primarily lack sufficient organic matter and the microorganisms needed to scavenge for and deliver nutrients to plants—in exchange for sugars and carbohydrates.[21,22]

Plants can manufacture their own sugars and carbohydrates through photosynthesis.[23] They combine the sun's energy with water and carbon dioxide, and use minerals provided by microbes in the process (e.g., manganese and calcium help split apart water molecules during photosynthesis; and iron aids in the synthesis of chlorophyll, which is also needed for photosynthesis).[24,25] Most of the resulting energy is directed to the plant's needs, but "excess energy" from photosynthesis—up to 20 percent of the plant's sugars, by some estimates—is fed to microbes in the root zone through plant exudates.[26,27]

Why would plants bother to feed these other organisms? Because in exchange for those sugars and other nutrients, plants acquire essential nutrients from the soil food web. Those soil microbes use enzymes to extract minerals from soil particles—sand, silt, and clay—as well as from larger particles (e.g., pebbles and rocks) that make up the "parent material" of soil. They also extract nutrients from the soil organic matter that is replenished regularly in a regenerative system. These microbial enzymes are like the superpowers that soil microbes bring to the table, to complement the plant superpower known as photosynthesis.

Some species of fungi and bacteria "infect" (not in the pathogenic sense of the word) plant roots and exchange nutrients with them from within the roots or through root hairs. These species are known as mycorrhizal fungi and rhizobacteria.[28,29]

Fungal hyphae can act like a transit system for nutrients and water. Some of those resources are shared with the plants that provided the exudates, by way of fungal hyphae that attach to the root system.[30]

There are also "free-living" bacteria in the soil—ones that don't inhabit a plant's root system but still provide nutrients to a plant, with fungi as their intermediary. This plant nutrition occurs through something called the "fungal energy channel,"[31] in which certain fungi associate both with plants and with bacteria that are nitrogen-fixing or can solubilize phosphorus.[32,33] This means it is not only legumes that can acquire nitrogen through an association with nitrogen-fixing bacteria; other plants receive nitrogen from free-living bacteria that channel this nutrient through fungi.[34]

A study published in 2018 describes another symbiotic process through which plants acquire nutrition. Plant pathologist James White from Rutgers University has described a "rhizophagy cycle" in which plants absorb microbes into their bodies and extract nutrients from them before returning those microbes to the soil to be recharged with nutrients.[35]

So far, science is unclear on what percentage of a plant's nutrition comes through each of these channels. But one thing is certain: All the processes described here put microbes at the center of plant nutrition. Moreover, even when plants acquire their nitrogen from applied fertilizers, much of this acquisition is microbially mediated.[36]

THE SOIL'S "PANTRY": FOOD WEB RETAINS NUTRIENTS

Most of the nutrients in soil ecosystems are bound up in mineral soil particles, dead organic materials, or in the living bodies of soil organisms. That doesn't mean plants can't eventually access those resources. Crucially, when these nutrients are bound up in the bacteria and fungi they will not leach out of the soil because they are not in solution, and because the bacteria and fungi have attached themselves to roots and organic matter.

Synthetic fertilizers are often delivered as liquids that are immediately available to the plant. However, what the plant doesn't take up is in danger of washing away in the next rainfall or irrigation event. That's why it is better to have nutrients stored in the soil's "pantry"—the mineral and organic materials and the soil food web—where they won't wash away, and they can be made available when plants demand them. Additionally, nitrogen is a mobile nutrient in soil, especially when it is in the form of nitrate, which is both the most leachable type of nitrogen and a form in which inorganic nitrogen is often delivered.[37,38]

If soil is aerobic, that means it has plenty of pore spaces and thus plenty of oxygen available for oxygen-loving organisms, such as plants and most fungi. Soils often go anaerobic when a compaction layer forms and causes water to build up in puddles at the surface, leading to erosion or waterlogging. If soil microbes have opportunities to create a loose, well-aerated soil—and heavy machinery, overgrazing, or tillage hasn't destroyed their work—the danger of losing nutrients to erosion is reduced or eliminated.

On the flip side, if a soil is compacted and highly anaerobic in some places, it sheds nitrogen, sulfur, and phosphorus as volatile gases, and can produce other toxic substances because anaerobic organisms have become more active. In addition, the aerobic organisms that build soil structure either die or go dormant when anaerobic conditions exist.[39,40,41]

Studies have also shown that soil microbial communities—and especially fungi—are important for the retention and delivery of key nutrients such as nitrogen[42] and potassium.[43,44]

THE CASTLE WALL: SOIL MICROBES GUARD AGAINST DISEASES AND PESTS

> *"Human pathogens account for much less than 1% of the total number of microbial species on the planet."*
>
> **—*Nature Reviews Microbiology* journal[45]**

Most microbial species are not disease-causing for plants or animals. In fact, most of the microbial species found in soil—or on plant parts—are beneficial or neutral to plants, animals, and humans. For example, some bacterial species create a protective layer of glues (slime) on plant surfaces, and fungi grow in these glues. Pathogenic microbes and insect pests find it difficult to penetrate the resulting "castle wall."[46]

Plants feed exudates to organisms that live on their surfaces both belowground (rhizosphere) and aboveground (phyllosphere—i.e., stems, leaves, etc.), and in exchange the plants receive protection from disease through four means: competition, consumption, inhibition, and induced resistance.[47,48,49,50]

- **Competition:** Aerobic bacteria and fungi will always outcompete anaerobic disease-causers for space on plant surfaces, so long as aerobic conditions are maintained.
- **Consumption:** Aerobic predators, such as predatory nematodes, show a preference for consuming anaerobic prey, and so help keep these organisms from proliferating. Again, conditions must be kept aerobic to allow these oxygen-loving predators to thrive.
- **Inhibition:** Certain species of bacteria[51] and fungi[52] produce antibiotics that chemically prevent competition and predation from other organisms. These compounds will be specific to a particular disease or pest, and their use is very localized.
- **Induced resistance:** Many bacterial and fungal species help a plant gear up to defend itself against diseases or insect predators. These microbes "sensitize the plant immune system for enhanced defense without directly activating costly defenses."[53,54]

MAKING WEEDS UNWELCOME: MICROBIAL ECOLOGY IS THE KEY

Every landscape is at some stage in the process of ecological succession. This is a natural process that can reset to the starting point if there is a serious disturbance, whether it be a flood, a widespread forest fire, a clear-cut or a tillage event.[55]

If a landscape is knocked back to the beginning of the ecological cycle—bare ground—the first plant species to take over in such conditions are plants we call weeds or pioneer species. At this stage of succession, the soil is dominated by bacteria, as most of the fungi will not have survived the disturbance. For example, their hyphal strands are chopped up by tillage equipment.[56,57]

Over time, other types of plants will supplant weeds as the dominant species in a landscape. The succession might, for example, lead through early- and mid-succession grasses; then late-succession grasses; followed by shrubs, vines and bushes; and eventually a mature forest.[58]

Along the way, different plant species will benefit from different organisms through the exudates they choose to release into the soil, as each exudate attracts different microbial species. In this way, plants are in essence designing a rhizosphere in which they can thrive.[59,60]

As the landscape moves along the successional gradient, the soil tends to become more fungal dominated because plants that are farther along on this gradient put out the complex foods that give fungi an advantage over bacteria. Fungal enzymes can break down compounds that are too complex for most bacterial enzymes to handle.[61,62]

Different crops will thrive at different places along the successional gradient because of changes in the relative biomass of fungi and bacteria. For example, the best conditions for growing brassicas, which include broccoli, cabbage, kale and turnips, would be soils dominated by bacteria. These crops associate with free-living soil bacteria for nutrient acquisition.[63] In some cases, fungi are the conduit that transfers bacterial-fixed nitrogen to plant roots. They deliver that nitrogen in the form of amino acids, which the plant then assembles into proteins.[64,65]

On the other hand, if you're growing grain crops such as corn, wheat, cereal rye, barley, or oats, these are late-succession grasses that form relationships with both fungi and bacteria. Grain crops form a symbiotic relationship with soil fungi for the sake of nutrient exchange.[66]

LET’S BREAK IT DOWN: SOME SOIL MICROBES CAN DECOMPOSE TOXINS

> *“Bioremediation is a biological process that uses living organisms, usually microorganisms (bacteria and fungi) and plants, to degrade, remove, alter, immobilize, and detoxify waste products and pollutants from soil or water.”*
>
> **—Mudasir Ahmad Dar, mycologist[67]**

Numerous fungal and bacterial species are adept at decomposing complex molecules, including pesticides.[68,69] Some white rot fungi, for example, “have the ability to degrade an extremely diverse range of recalcitrant or toxic environmental pollutants,” such as polycyclic aromatic hydrocarbons (PAHs), pentachloro-biphenyls (PCBs), and fluoroquinolone antibiotics.[70] These fungi produce a wide array of enzymes that, in the forest, break down the complex components of wood, mainly cellulose and lignin. The latter has 201 atoms in each molecule, so breaking it down requires strong enzymes.[71,72]

Those same enzymes translate into bioremediation value for white rot fungi, as well as other fungal and bacterial species, when the task at hand is to break down or otherwise alter toxins in the soil. This could have relevance for anyone trying to regenerate land that has been degraded by agrochemicals or other toxins.[73,74,75]

GROW MORE FUNGI, ACCUMULATE MORE CARBON

While they are good at breaking down complex compounds, fungi also *create* complex compounds as part of their biology. These compounds—which form the cell walls in their previously discussed hyphae—are mostly made up of complex carbon molecules. The carbon-to-nitrogen ratio in fungi can be as low as 4:1 but can range as high as 50:1, especially in older hyphae.[76,77] These substantial concentrations of carbon make fungi a prodigious storehouse for the very element that society wants to draw down from the atmosphere because its high concentration there is linked to chaotic climate change.[78] Contrast this with bacteria, whose bodies typically hold much less carbon.

The fact that fungal cell walls are complex makes them more resistant to decomposition. One study estimated that mycorrhizal fungi "receive the equivalent of 13 billion tons of carbon dioxide annually from plants—equal to 36% of current annual fossil fuel emissions."[79,80] Plant scientist Katie Field, a co-author on that study, has commented that "mycorrhizal fungi represent a blind spot in carbon modeling, conservation, and restoration," and one of her co-authors, Merlin Sheldrake, added, "Many human activities destroy underground ecosystems. Besides limiting the destruction, we need to radically increase the rate of research."[81]

Hannula, et al., have commented:

- "Extensive or regenerative farming usually favours the fungal [energy] channel and enhances the carbon accumulation."
- Fungi generally have a higher [carbon use efficiency] than bacteria.
- Fungi contribute approximately 20% more to [carbon] storage in agricultural soils compared to bacteria.[82]

Given that fungi are storing this much carbon in a world where most of our farming is destructive to fungi, imagine how much carbon these organisms could store if our mainstream farming methods actually helped them thrive.

The aforementioned glue known as glomalin—produced by mycorrhizal fungi—has been said to account for “27 percent of the carbon in soil,” as well as to reduce the breakdown of organic matter, and to persist in the soil for decades.[83] A lot of studies correlate fungi and glomalin with greater carbon storage.[84,85,86,87]

INDUSTRIAL FARMING BREAKS UP A BEAUTIFUL PLANT-MICROBE MARRIAGE

> *"If we understand better how plants work—how they use these microbes to do what they need to do— then it makes more sense for us to change how we do agriculture."*
>
> **—James White, plant pathologist[88]**

Methods that predominate in industrial agriculture tend to diminish or destroy the soil food web and therefore undermine the benefits described earlier, such as structure, aeration, nutrient cycling, and disease suppression. These destructive methods include tillage, the use of agrochemicals, and monocultures.[89]

Tillage

Tillage is not only used in conventional agriculture, but also in most organic systems (which do forgo the use of most synthetic chemicals). In either case, the practice destroys much of the soil's biology, and in particular fungi, because it chops up the fungal hyphae that create a network to deliver nutrients to plant roots.

How else does tillage harm soil life? Let us count the ways:

- It creates a compaction layer that deters or fully prevents plant roots from penetrating deep into the soil.[90]
- In these compacted areas, tillage has conferred a competitive advantage upon anaerobic microbes instead of the aerobic microbes that create a more plant-beneficial soil food web and perform the essential functions described earlier.
- These anaerobic microbes (many pathogenic) tend to produce methane and other gases as part of their anaerobic breakdown of organic matter.[91,92,93]
- Tillage sets the stage for disturbance-loving weeds, which do not typically put out as many exudates as plants that are farther along in succession. Post-tillage, there is also less living

biomass on the soil surface (especially right after tillage when the field is reduced to bare soil), so resident microorganisms typically have access to fewer food sources.

- Initially, tillage creates a feeding frenzy among certain species of soil bacteria, as they take advantage of the additional exposed surface areas among the diced-up organic matter (OM). However, over the long haul there will be less OM available to the "microherd" that feeds on it, because plant biomass has been reduced and the feeding frenzy will have used up available OM too quickly.[94,95]
- Tillage leads to more evaporation from soil, meaning less water is available for both plants and microbes.[96]

As with any general principle, there are exceptions, and the no-till "rule" is no different. There are circumstances where tillage makes sense, especially where compaction is so great that the soil biology needs a bit of help as it repairs previous damage. This kind of tillage can be a one-time event, though, or a rare one. It can also be used as an opportunity to inject needed biology into degraded soils.

If tillage is to be a more regular event, it can work if farmers are being more targeted and only tilling a narrow furrow where seeds will go, as opposed to tilling an entire field. Some systems use a mix of annual and perennial crops, in which the perennials keep the microbiome fed all year long.[97,98,99]

Synthetic fertilizers

> *"The scientific basis for input-intensive cereal production is seriously flawed. The long-term consequences ... will be a decline in soil productivity that increases the need for synthetic [nitrogen] fertilization, threatens food security, and exacerbates environmental degradation."*
>
> —Richard L. Mulvaney, soil scientist [100]

The global market for synthetic, inorganic fertilizers for farming has been valued at nearly $84 billion per year, and it is expected to grow by more than 30 percent in the next decade.[101]

You don't have to search long and hard to find people who will tell you that farmers need synthetic fertilizers to maintain or increase yields. This dogma has driven a significant increase in synthetic nitrogen use since 1960. That year US farmers were buying about 17 pounds per acre per year, but by

2013 that number had increased to 84 pounds per acre.[102] Nitrogen represents about 60 percent of all fertilizers applied in the US, with phosphorus and potassium representing most of the remainder.[103]

Synthetic nitrogen is particularly prone to leaching through the soil or volatilizing and being lost to the atmosphere. Estimates of how much nitrogen fertilizer is actually taken up by a crop can range from 50 percent at the high end to as little as 12 percent. This low-level uptake is not surprising when we consider that if plants are to take up nutrients without the aid of microbes (in an abiotic way), that means the nutrient must be in a soluble form and come in contact with the plant's roots. Plants can't reach out and grab nutrients that are beyond their roots—the microbial network must do that for them.[104,105,106]

Research has shown that nitrogen fertilizers actually deplete soil nitrogen. So, one could say the main factor driving the "need" for synthetic fertilizers is the very use of synthetic fertilizers—a self-perpetuating loop that is only fortuitous for that input industry.[107,108]

This dilemma has been summed up thusly:

> *"The environmental consequences of synthetic chemicals compromising symbiotic [i.e., biological] nitrogen fixation are* ***increased dependence*** *on synthetic nitrogenous fertilizer, reduced soil fertility, and unsustainable long-term crop yields."* **[emphasis added]**[109]

"Microbes are freeloading couch potatoes when [synthetic] nitrogen is around," says Karsten Temme, a bioengineer and CEO of Pivot Bio, a biotech company. "If the soil has synthetic fertilizer, bacteria will use that rather than pull nitrogen from the air. That requires farmers to use more fertilizer to have the same effect on crop yields."[110]

By using synthetic fertilizers, farmers are disrupting the ages-old symbiosis between plant and microbe that leads to nutrient cycling in a healthy soil and replacing it with a sort of chemical dependency. This disruption may also linger when farm fields have been given inorganic nitrogen for many years, as this long-term use produces "a long-lasting inhibitory effect on plant access to organic [nitrogen] sources, with potential consequences for agricultural productivity," according to one study.[111] These long-lasting effects mean farmers must wean themselves off synthetic nitrogen for two to three years—as they wait for the soil food web to rebuild itself—rather than going cold turkey.

The symbiosis between plants and soil microbes (e.g., I'll trade you my sugars for your minerals) goes back hundreds of millions of years. Synthetic fertilizers—which disrupt this ancient symbiosis—have been in common usage for less than a century.[112]

Tripathi et al. describe some of this disruption: "Synthetic fertilizer application begins the destruction of soil biodiversity by suppressing the role of nitrogen-fixing bacteria and enhancing the role of everything that feeds on nitrogen. These feeders then amplify the decomposition of organic matter. As organic matter decreases, the physical structure of soil typically degrades."[113]

If the soil food web is functioning normally, plants do not need synthetic fertilizers to thrive. In fact, those fertilizers only tend to show a yield benefit when they are applied to soils that have very little biological activity in them—in other words, something that is more like dirt than soil. Because the plants in those degraded soils are unable to acquire nutrients in the normal way, they respond to nitrate applications. Farmers see yield gains in these cases, but not when synthetic, inorganic fertilizers are applied to soils that have abundant biology.[114]

Lastly, all inorganic fertilizers are salts, and the accumulation of these salts in soils eventually compacts and degrades the soil. The long-term effects have been described thusly:

"The excess mineral salts alter the physical properties of the soil ... The fine and structureless salts present in the fertilizers cover the soil surface and hinder water percolation. As a result, a hard and impermeable layer develops [hardpan]. The resulting soil compaction causes severe complications ... which affect the natural nutrients/water uptake capability of plants ... ultimately resulting in stunted plant growth and low productivity."[115]

Pesticides

The global market for agricultural pesticides has been valued at about $100 billion and is growing.[116] While many pesticides have been linked to cancer and other diseases in humans,[117] we are often told that they are, at the very least, a necessary evil if we are to grow enough food to feed everyone.

However, as with synthetic fertilizers, the "need" for pesticides is also created by their very use. When they kill pests through chemical means, farmers are also destroying the natural enemies of those pests, which includes the bacteria and fungi that protect plants (the "castle wall"). Now that their natural defense system has been knocked down, plants appear to need pesticides for defense.

Not surprisingly, the chemicals designed to kill target organisms (pests) can also kill soil microbes or damage their DNA.[118,119] When they do so, we lose some of the soil food web functions outlined earlier.[120] In addition, pest species invariably recover from pesticide applications faster than the species that prey on those pests.[121] Risk assessments of pesticides do not consider their broadly negative effects on soil microbes.[122]

Research has shown that "one of the environmental impacts of pesticides and contaminants in the soil environment is disruption of chemical signaling between host plants and [nitrogen-fixing bacteria] necessary for efficient [symbiotic nitrogen fixation] and optimal plant yield." In other words, pesticide use can also set the stage for plants to need synthetic fertilizers.[123,124]

Additionally, without that chemical signaling from beneficial microbes, plants do not get the message to gird themselves against potential pathogens.[125]

The herbicide glyphosate offers an important case study, as it demonstrates how pesticides can harm the soil food web and the plant-microbe symbiosis. Glyphosate has been called "the most extensively used herbicide in the history of agriculture." It has been most famously marketed as Monsanto's Roundup and paired with "Roundup-ready" crops such as corn, soy, and cotton.[126]

Some of glyphosate's impacts:

- It bonds with important minerals in the soil, rendering them less available to plants. This is not surprising because, before its herbicidal qualities were discovered, glyphosate was known to be a chelator (a chemical that bonds with metals). As Mertens, et al., explain:
    - "Glyphosate ... binds macro- and micronutrients and can impact their uptake and availability in plants treated with glyphosate-based herbicides ... In particular, availability of micronutrients such as iron,

manganese, zinc, copper, and nickel may be affected."[127]

  - To choose just one example from that nutrient list: Recall that manganese is an essential ingredient in photosynthesis, among other functions within a plant. Reducing its availability can mean reducing the photosynthetic capacity of any crop.[128,129]
  - Meanwhile, "iron deficiency is increasingly being observed in cropping systems with frequent glyphosate application."[130]

- Glyphosate reduces populations of beneficial microbes—including several species of *Pseudomonas* bacteria, which help with plant growth, solubilizing nutrients, and degrading toxins, among other things—and increases populations of pathogenic microbes such as the fungus *Fusarium*.[131,132]
- It has indirect effects on plant, animal, and human immune systems because it alters the species mix of microbiomes, both in soil and in the intestinal tracts of animals and humans.[133,134]

- It disrupts interactions between earthworms and mycorrhizal fungi and reduces the colonization of root systems by these symbiotic fungi.[135]

Monocultures

Industrial agriculture has stressed monocultures as a hallmark of efficiency, but this kind of factory-like efficiency (produce one thing well) does not carry over well to natural environments. A monoculture's lack of diversity aboveground is mirrored by a lack of diversity belowground, and this makes for an agroecosystem that produces less biomass than a diverse one.[136]

Conversely, regenerative agriculture methods such as cash crop mixtures and cover crop mixtures lead to diversity in the soil microbiome, because different types of plants associate with different types of soil microbes.[137] Compared to monocultures, these diverse agroecosystems accumulate more carbon,[138] increase ecosystems' resistance to weather extremes,[139] and make them less prone to disease.[140]

Additionally, crop diversity leads to increased collaboration among the soil's microbial inhabitants.

Through chemical messaging that can span diverse microbial species,[141] the microbiome can sense how much diversity is nearby. When it senses that the nearby microbiome is very similar to itself, it sees that microbiome as a competitor instead of as a potential collaborator.

"If we have two corn plants or two wheat plants growing side by side, they're ... probably going to have identical microbiomes, and that's going to have a negative feedback effect on plant productivity," according to Australian microbiologist Christine Jones.[142]

On the other hand, if the neighboring microbiome is dissimilar, the microbiome in question will now be willing to cooperate with its neighbor. Why, you ask? Jones explains this differential behavior by comparing a native prairie to a monoculture:

"If there is something in that plant community that is able to grow at most times of the year ... there is energy coming into that microbial network continuously, year-round ... If you only have one kind of plant there, it's only going to grow productively at one time of the year or under one set of environmental conditions, and for the rest of the year the microbes in the soil basically starve. So, **it is to the benefit of the soil microbial community to have as many different kinds of plants there as possible**, and the microbial community at some level is able to detect that." **(emphasis added)**[143]

Jones stresses that crop mixes should include different plant families—not just different species from the same plant family—as this makes an ecosystem diverse in terms of functional traits. This approach mimics the type of plant community found in a prairie.

REGENERATIVE FARMING EMPHASIZES THE SOIL FOOD WEB

> *"When I asked [soil scientists] about this thing that I'm going to work on—the bacteria and the fungi in soil—they said, 'they don't really do anything.' "*
>
> **—Elaine Ingham, soil ecologist[144]**
>
> *"Microbes form the backbone of every ecological system on Earth by controlling biogeochemical cycling of elements essential for life, such as carbon and nitrogen."*
>
> **—National Library of Medicine[145]**

Elaine Ingham began her work on soil microbes in the late 1970s[146] and went on to coin the phrase "soil food web" to describe the microbial players in the soil ecosystem and their functions and interactions. Despite her findings and those of other researchers, the mainstream of agriculture has continued to mostly ignore soil microbes. It made sense that it would do so, as an entire industry has been built up around the idea that synthetic N-P-K (nitrogen-phosphorus-potassium) were all farmers needed to fertilize their crops effectively. The role of microbes in delivering to plants those macronutrients, plus a bevy of essential micronutrients, has not been a point of focus.

However, there is a growing group of farmers and ranchers who recognize that nurturing a healthy soil food web is essential to producing the healthy crops and healthy food animal products that are needed if humans are to thrive. Their biological approach can solve three of the largest dilemmas that any farmer faces: dealing with weeds; maintaining fertility; and defending against pests and diseases.

We've discussed how industrial agriculture addresses this triumvirate of problems with tillage/herbicides, synthetic fertilizers, and pesticides—all of which produce significant and negative side effects, including harm to soil microbiomes. Let's now look at how regenerative agriculture tackles these same issues without tearing up the landscape or spreading toxins.

Weeds

> *"It's about creating an environment where weeds don't want to germinate and grow."*
>
> —Rick Clark, regenerative farmer[147]

One of the toughest challenges in farming is to grow crops without using chemicals and without tilling, and still keep weeds under control. One farmer who has achieved that goal is Rick Clark, who farms 7,000 acres in Indiana. Clark uses cover crops to suppress weeds, and rather than till in those cover crops to make room for his cash crops—or spray herbicides to kill weeds—he uses one pass through his fields to both roll down the cover crop with a roller crimper[148] and plant his cash crop into the stubble.[149]

Clark's cover crop mixes create fields that are diverse both above- and belowground. They typically include five plant species with diverse functional traits (e.g., one plant to fix nitrogen, one to reduce compaction, one to build biomass, and one to encourage growth of mycorrhizal fungi). This spurs diversity in his soil's microbial community.[150]

This relationship between plant diversity and soil microbial diversity has been validated by a long-running field study in Germany known as the Jena Experiment. Its researchers have commented that Jena "has contributed to the overall conclusion that biodiversity *per se* is an important driving factor of ecosystem functioning including important variables such as production, nutrient cycling, [and carbon] storage."[151]

Crop mixtures can also help suppress weeds. For example, in a three-year study covering 31 sites in Canada and Europe—which varied greatly in terms of average temperatures and rainfall—researchers found that "average weed biomass across all grass-legume mixtures was 52% less than in the most suppressive monoculture."[152]

It's worth noting that Clark's farm is not just an ecological success. He is also putting more money in his pocket because he saves so much on input costs—about $2 million a year by his own reckoning, which he used to spend mostly on synthetic fertilizers and pesticides. He has reduced his use of these inputs to zero, while also reducing his diesel fuel use by making fewer tractor passes through his fields.[153,154,155]

In an era when most Indiana farms are growing only corn and soybeans—and only one of those at a time—Clark's farm is always growing at least eight crops at any one time. He mimics nature's diversity and reaps benefits from it.[156]

Fertility

> *"The future of agronomy and plant nutrition will be based on understanding the science needed to supply one hundred percent of a high yielding crop's nutritional requirements as microbial requirements, and not as simple ions from applied products."*
>
> —John Kempf, executive editor of *Acres U.S.A.* magazine[157]

The success of many regenerative farmers belies the notion that synthetic fertilizers are essential to farming success. Farmers who were once heavily dependent on synthetic nitrogen have weaned themselves off this input in a three-year process that allows the plant/microbe symbiosis to ramp up again.[158,159]

The question of fertility can be recast as a question of plant nutrition, once we acknowledge that any soil—whatever its proportions of clay, sand and silt—can be made fertile if we restore a thriving soil food web along with soil organic matter reserves. Remember, the mineral elements are usually present already, but microbes are needed to help plants access them.

Nitrogen is often cited as the "limiting factor" in agriculture—the thing that keeps us from achieving maximum crop yield. This is ironic, since nitrogen makes up 78 percent of the atmosphere. However, this atmospheric nitrogen cannot be directly accessed by plants; it is in the form of N2, a triple-bonded molecule that is hard to break apart. This all seems like a cruel joke that nature is playing on plants. However, there is an intermediary in the soil that can break those nitrogen bonds and feed that nutrient to plants: bacteria.

Despite the existence of this biological source of nitrogen, farmers hear a constant drumbeat of marketing that tells them they must bring in synthetic nitrogen as an external input. But, if their farming system supports the associations among bacteria, fungi, and plants—which includes the acquisition and delivery of nitrogen in the form of amino acids—this "necessity" for synthetic nitrogen is greatly reduced or eliminated. It is also better for plants to receive nitrogen in the form of amino acids (that is, from microbes) rather than as nitrates, as this saves them the energy required to assemble the nitrates into amino acids.[160,161]

Once farmers accept that natural fertility is driven by plant/microbe symbiosis and not by a bag of synthetic fertilizer, they are set up to view biological inputs as the answer to long-term fertility. These biological inputs (e.g., compost, compost extracts, manures) inject microbes, organic nutrients, and carbon compounds into soil and support plant/microbe symbioses. Those microbes are a self-replicating amendment, so they are much kinder to a farmer's bottom line than inputs that require increasing application rates and more frequent applications. Once biology-focused farmers regenerate their soil microbiome, they need few additional inputs.

Along with nurturing a greater volume and diversity of soil life, farmers should also be paying attention to the relative abundance of fungi in their soil.

Microbiologist David Johnson and his wife, Hui-Chun Su Johnson, created a composting system—the Johnson-Su bioreactor—that produces a fungal-dominated product. They tested their compost against eight other composts from their area of New Mexico and found that it produced at least twice the plant growth of any of its competitors. This result could be confounding to some observers, because the Johnson-Su compost had very low levels of nitrogen, phosphorus, and potassium, the N-P-K triumvirate that would be expected to correlate with good plant growth. Instead, what correlated most with plant growth in their study was fungal abundance.[162]

They then tested how much of the carbon captured through photosynthesis was flowing to plant biomass (roots, shoots, and fruits) in different scenarios. They found that increasing the fungal biomass translated into greater efficiency in plant growth. When compared to the fungal biomass that is typically found in conventional farm soils, the highest fungal abundance in the experiment was five times as efficient in terms of carbon being directed into plant growth, and even outperformed the most productive natural ecosystems in terms of carbon capture.[163]

Pests and diseases

> *"I used to wake up in the morning thinking about what I'm going to kill today: a fungus, a weed, a pest. I was going to kill something. Now I wake up thinking how I'm going to get more life on my operation. It's a lot funner working with life than with death."*
>
> —Gabe Brown, regenerative farmer[164]

Chemical agriculture applies a very simple logic to pest management—see a pest and devise an intervention (usually a pesticide) that will kill that pest. It doesn't look at all the other species in an agroecosystem—including predator insects—and the impact that a chemical intervention might have on those species.

Meanwhile, as with plant nutrition, there is a long-standing relationship between plants and microbes that aids plants in their defense against pests and disease. There are also natural predators that can keep pests in check. Regenerative agriculture responds to pests by:

- Thinking in a more system-wide way about what is causing a pest problem, by looking at an entire agroecosystem and considering the likely impact of any chemical on non-target species. It also tries to mimic nature in designing responses.[165,166]

- Enlisting natural enemies of pests to keep them in check (biocontrols), either by introducing these predators to the farm as an external input or by creating habitat that attracts them.[167,168]
- Using companion plants that deter pests, or planting "trap crops" that serve as a sacrifice zone and mean less predation on cash crops.[169]
- Understanding pest life cycles and intervening to disrupt those cycles with non-toxic methods such as crop rotations (creating a collateral benefit, in addition to all the other benefits of crop rotations).[170]

If all these steps fail, there are organic biocides that farmers can try before resorting to synthetic chemicals.[171]

The best way, though, to avoid having pest problems in the first place is to nurture the microbes that create a castle wall to protect plants from pests and disease. Soil microbes also provide minerals that are involved in disease suppression, so harming soil life can degrade this aspect of a plant's immunity.[172] Microbes also provide minerals that are needed for photosynthesis, and a plant's photosynthetic rate affects its ability to defend against pests and disease. When a plant has a sufficient photosynthetic rate, it can devote the necessary energy toward immune response, while also meeting all of its other energy needs. It has been shown that being connected to mycorrhizal fungi improves a plant's photosynthetic performance.[173,174]

As discussed earlier, microbes help warn plants of pest and disease threats through chemical signaling. Common mycorrhizal networks—by which fungal hyphae "connect the roots of multiple plants of the same or different species belowground"[175]—have been shown to "facilitate defense against insect herbivores and foliar [parasitic] fungi by acting as the conduits for interplant signaling" and triggering the expression of defense genes.[176]

Taking the long view of this relationship between plants and pests that prey on them, we might ask how plants defended themselves before there were chemicals designed for this purpose? The answer: Biodiversity was their best defense, because that biodiversity includes predator species that keep pest populations in check, and a host of microbes involved in plant immunity. Some research supports the idea that increased biodiversity means lower pest populations.[177,178]

CARBON IN, CARBON OUT: A HEALTHY MICROBIOME SHIFTS THE BALANCE

> *"The movement of carbon from the atmosphere to soil—via green plants—represents the most powerful tool we have at our disposal for the restoration of soil function and reduction of atmospheric CO2 ... An increase of around 5 percent in global photosynthetic capacity and/or photosynthetic rate would be sufficient to counter the CO2 flux from the burning of fossil fuels."*
>
> **—Christine Jones, microbiologist[179]**

Soil is recognized as a significant carbon sink. The National Academy of Sciences says the world's soils are holding three times as much carbon as the atmosphere and four times as much as vegetation.[180]

Here are two important terms to understand while discussing this carbon sink: Soil organic matter (SOM) and soil organic carbon (SOC). SOM has been described as "the portion of soil that is composed of living and dead things in various states of decomposition."[181] Since all living things contain carbon, it is not surprising that SOM is made up of 50 percent carbon.[182,183]

Even many conventional growers pay attention to the level of organic matter in their soils—so, by extension, the level of organic carbon—but many have seen that level decline over time because of practices like conventional tillage. It has been estimated that US soils alone "may have lost between 30 and 50 percent of the [soil organic carbon] that they contained prior to the establishment of agriculture there."[184]

Much of this carbon has ended up in the atmosphere, but it could be returned to our soils if we transitioned from farming practices that undermine the soil microbiome to ones that nurture it. Doing so would create obvious benefits for addressing our climate crisis, but it would also benefit farmers by making the soil more productive.

Carbon from photosynthesis is the engine that drives the microbiome to greater heights of nutrient cycling and soil formation. Through photosynthesis, plants take carbon out of the atmosphere and put much of it into the soil. That's two good things happening at once, and it helps solve two problems humans are struggling with: The excess carbon in our atmosphere, and the deficit of carbon in our soils.

To be clear, carbon is forever entering and leaving any agroecosystem, as part of the carbon cycle. What matters is the balance between these "carbon in" and "carbon out" phenomena. Improving the soil microbiome can increase the rate at which that microbiome stores carbon and decrease the rate of carbon respiration. Specifically, increasing the soil's fungal biomass has these effects.[185]

That is what microbiologist David Johnson has concluded through his field trials in the New Mexico desert. The Johnson-Su bioreactor[186] produces a fungal-dominated compost that increases the fungal abundance in a soil. Johnson found that this increased fungal content raised both the soil's rate of carbon accumulation *and* its rate of respiration. But crucially, the respiration rate only doubled while the accumulation rate increased by seven times.[187]

These results are not entirely surprising when we recall that fungi typically have a much higher carbon-to-nitrogen ratio than bacteria. Because they need less carbon in their bodies than other organisms, bacteria put out more carbon as a waste product. If there is not a good microbial balance in the soil—whereby other soil microbes absorb carbon wastes from bacteria—more of that carbon ends up in the atmosphere than would otherwise be the case.

Johnson's compost is one component of a farming system he calls BEAM—Biologically Enhanced Agricultural Management. BEAM practices also include reducing or eliminating chemical inputs and tillage; keeping the ground covered with plant life year-round; and a carefully managed grazing program.[188]

Johnson has reported that his BEAM system outperformed other tests of soil carbon storage potential by between 15 and 50 times, as it captured 10.7 tons of carbon per hectare per year, compared to similar research that reported carbon-capture potential of between 0.2 and 0.7 tons per hectare.[189,190,191,192]

Johnson also reported that a one percent increase in his soil's organic carbon increased the soil's water-holding capacity by five times.[193] This generally concurs with other research on increased water-holding capacity associated with soil organic carbon.[194]

That brings up an important component of our climate problem: water vapor. Just as we have seen a decrease in the organic carbon in our soils, there has been a concomitant decline in the amount of water that our soils are holding. Not surprising, since all of the living things in the soil need water and will always be holding onto some of it—so, if there is less life in the soil, there will also be less water.[195]

As with carbon, much of the water "lost" from soils has ended up in the atmosphere. This exacerbates the climate crisis, as water vapor is underappreciated as a contributor to the planet's warming. According to NASA: "Water vapor is Earth's most abundant greenhouse gas. It's responsible for about half of Earth's greenhouse effect." The space agency also reports that "increased water vapor in the atmosphere amplifies the warming caused by other greenhouse gases."[196]

So, soil degradation leads to an increased release of two greenhouse gases into the atmosphere: carbon and water vapor. Additionally, when degraded soil becomes compacted and anaerobic conditions result, anaerobic organisms in the soil produce more methane, a potent greenhouse gas.[197]

SUMMARY: WE CAN'T JUST SUSTAIN; WE MUST REGENERATE

> *"Life is an interplay between organic and inorganic constituents ... For the last century we have approached agriculture from a predominantly inorganic perspective. It may be time for us to better explore the organic portion and begin considering using biology to help solve some of our problems."*
>
> **—David Johnson, microbiologist**[198]

The Chemical Age of Agriculture has greatly harmed soil microbes—and therefore soil ecosystems. This damage has had a cascading effect on farms, rural economies, and rural communities. But that's putting the negative spin on this story. The positive spin would point out that if agriculture became attuned to the needs and the functions of soil microbes, this would open up enormous possibilities for improved agronomic, ecologic and economic outcomes.

Before the first synthetic chemical was applied to a farm field, plants and microbes were not waiting around for this technological advance to happen. Over millions of years, they had evolved ways to thrive in all kinds of conditions. We should develop a greater trust in the efficacy of the natural systems that provide plant nutrition and plant defense, and a greater understanding of how our current mainstream methods are undermining these systems.

Science could abet our crucial farming transition by continuing to study the soil microbiome, its relationship to plants, and how we can further enhance this relationship to achieve better outcomes on all fronts. A biological input industry could grow alongside a growing regenerative sector, but farmers would not be spending nearly as much on these inputs compared to the current chemical regime. Many farmers could source these inputs locally or produce them on-farm.

Much has been said about the need to create a sustainable agriculture, but we can—and must—reach beyond that goal by creating a regenerative agriculture that undoes and reverses the damage done by tillage, synthetic chemicals, monocultures, and other methods. This sounds daunting, but there are already farmers who have shown us the proof of concept: that farmers can eschew these chemical "solutions" in favor of an agriculture that nurtures soil biology and thus solves the biggest problems in farming without creating environmental damage or public health risks. In this way, farming can do more than just stem the tide of environmental damage; it can become a force for ecological restoration and climate improvement.

The farming models needed to produce food that will keep our population healthy depend on nurturing instead of destroying the natural resource base on which farming is founded. Farming must nurture microbes in the soil, so they can perform important functions, such as building the soil structure that allows for good water infiltration and retention; acquiring, cycling and retaining nutrients; and protecting plants from diseases and pests.

In regenerative agriculture, it is first and foremost the *soil ecology* that is being regenerated. Creating a healthy soil food web is essential to producing the healthy crops and healthy food animals that are essential to human health. The follow-on benefits include the regeneration of landscapes, local economies, and communities.

In other words, belowground success ignites aboveground success.

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CENTER *for* A LIVABLE FUTURE

Successful farming doesn't just start at the ground level. It starts belowground, where the soil's tiny inhabitants do unsung work that is essential if crops are to thrive. Beneficial bacteria and fungi not only establish the soil habitat by creating a porous structure there, but they also help our crops obtain nutrients and defend themselves against pests and disease. However, the heavy tillage and prodigious chemical use that are standard in industrial farming degrade this soil ecology and diminish its vital functions. Regenerative agriculture, meanwhile, gives appropriate attention to these soil allies, and offers potential for a brighter farming future.

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