Getting Back to Our Roots
Agriculture Rediscovers the Living Soil

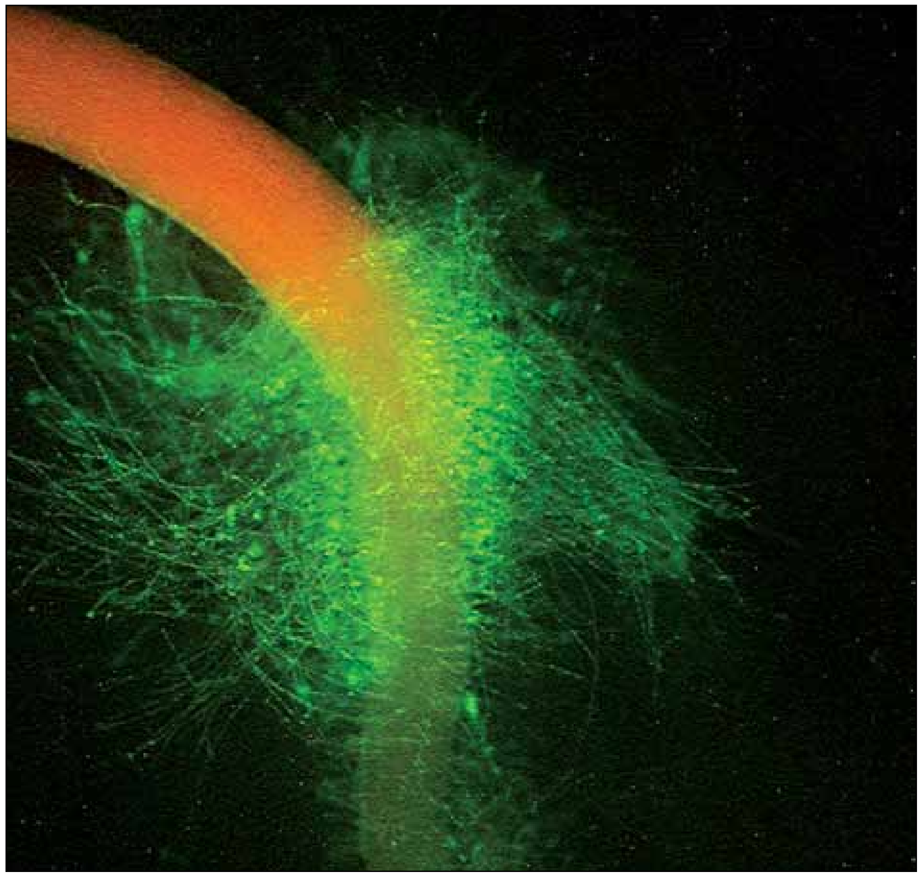
by Michael Amaranthus, Ph.D.

Ten years ago you had not heard of the "blogosphere." Now the term is everywhere. But you probably have not heard of the sphere that you have been walking upon all your life: the "pedosphere;" the thin envelope surrounding the Earth's surface where soils occur and where soil-forming processes are active. It's time to change that. Perhaps the single greatest leverage point for a sustainable lifestyle for the 7 billion people on the planet is immediately underfoot — the living soil, where we grow our food.

The thin layer of living soil is the "skin" of the Earth and, like your own skin, it is constantly forming and changing. It is composed of soil, existing at the interface of the atmosphere (the air within and above the soil), the lithosphere (the Earth's crust), the hydrosphere (water within, on and below the soil) and the biosphere (all living organisms).

The soil is home to the most populous community on the seven continents — the soil micro-biome. Ninety percent of all organisms live underground. There can be 10,000-50,000 species in less than a teaspoon of soil. In that same teaspoon of soil, there are more microbes than there are people on the Earth. In a handful of healthy soil, just the bacterial community contains more biodiversity than can be found in all the animals of the Amazon Basin (Figure 1).

Figure 1



Root and rhizosphere

This hidden world represents the foundation of terrestrial life on this planet; it's the source of nearly all our food. Yet the way we grow our food, the way we use the soil resource is unsustainable. We have a *growing* problem. Mass damage is occurring in agricultural soils through overuse of certain chemicals, tillage, recurring fallow, soil erosion and the failure to add organic matter — upon which most microorganisms feed. Half of the Earth's habitable lands are farmed. We are losing soil and organic matter at an alarming rate (Figure 2). Studies show steady global soil depletion over time and a serious stagnation in crop yields. A majority of the quintillions of microbes that thrive in healthy soil have been rendered inactive or eliminated in degraded soils, no longer able to do what they have done for hundreds of millions of years — conserve and cycle nutrients and water for plants and regulate the climate.

So not only have we stopped natural processes of sequestering carbon in arable land, but agriculture has become one of the biggest causes of climate instability. Our current global food system, from fertilizer manufacture to food storage and packaging, is responsible for up to one-third of all human-caused greenhouse-gas emissions. This is more than contributed by all the cars and trucks in the transportation sector and accounts for about one-fifth of all greenhouse gases globally.

Surprisingly, in an age when knowledge has exploded, overall soil ecology still holds many mysteries. The greatest unexplored frontier is arguably beneath us. What Leonardo Da Vinci said 500 years ago is arguably still true today: "We know more about the movement of celestial bodies than about the soil underfoot."

Our very concept of agriculture may be a rather limited notion. The word agriculture came from two Latin roots, *agri*, genitive of *ager* "a field" and *cultura* "cultivation" in the sense of tilling. But the living soil is much more than a field. And agriculture is far more than tilling a field. We must look below the surface. The solution lies deeper — by understanding soil in the context of a living

Figure 2

Degraded agricultural land

system that combines minerals, organic matter, water, air and living organisms.

There is good news, however. We have made technological advances and can take economically and politically feasible steps right now to replenish the soil — specifically the natural microorganisms that cycle nutrients and water for crops, improve root health, build soil structure and regulate the climate by sequestering massive amounts of carbon.

UNDERGROUND & UNDERVALUED

By many calculations, the living soil is the Earth's most valuable ecosystem, providing ecological services such as climate regulation, mitigation of drought and floods, soil erosion prevention and water filtration that are worth trillions of dollars each year. The soil is a critical form of natural capital that continues to give us massive value.

The natural capitalism perspective establishes economic value in the environment. It is a perspective that accounts for the value of nature's provision of climate, food, water, energy and health security. If we do not degrade the soil, it can yield a sustainable flow of valuable ecosystem services far into the future. The microscopic bacteria and fungi underfoot have real economic value, estimated in the trillions of dollars. To create a sustainable agricultural future, the soil should be the last place we degrade resources and the first place we look for inspiration.

Yet, we tend to take this great source of natural capital for granted. Just like our heart, which pumps day in and day out, providing us with life-sustaining services, it sends no bill. The soil has been working for us, and we have not paid for it. The services it provides never show up in the accounting systems of modern agribusiness. In fact, we have not taken it into account and we have spent it recklessly on many lands. For far too long we have taken the soil for granted, and, to put it bluntly, treated it "like dirt."

Most people in developed countries today are completely out of touch with the soil; it's the source of our food, an integral link to environmental quality, climate, and our future. It is so easy to forget that we cannot exist without the complex ecological system contained in the living soil. It is our ultimate source of health. We now read more and more about the human micro-biome — those microbial communities found on our body, in our nasal passages, mouth, throat, skin, gastrointestinal tract and urogenital tract is critical to our health. We are covered and filled with microorganisms: the human body contains over 10 times more microbial cells than human cells (collectively they weigh about three pounds — the same as our brain). So why are we so surprised to learn that plants also depend on microbes in the soil to maintain their health and vigor? Some microbes pose threats to us in the form of diseases, but the vast majority of them are vitally essential. Microorganisms digest our food, regulate our systems and ward off deadly pathogens and so it is with plants and soil microbes.

AN EMERGING INDUSTRY

Biological agriculture based on a living soil is already delivering value to customers in two different categories. Bio-fertility products are a $500 million industry. These include inoculants that allow for the efficient use of nutrients or boost the yield of crops. Bio-Pesticides are a $1.5 billion industry. These include bioherbicides, biofungicides and bioinsecticides. An example of biofertility products are those containing *Rhizobium* bacteria that allow the conversion of

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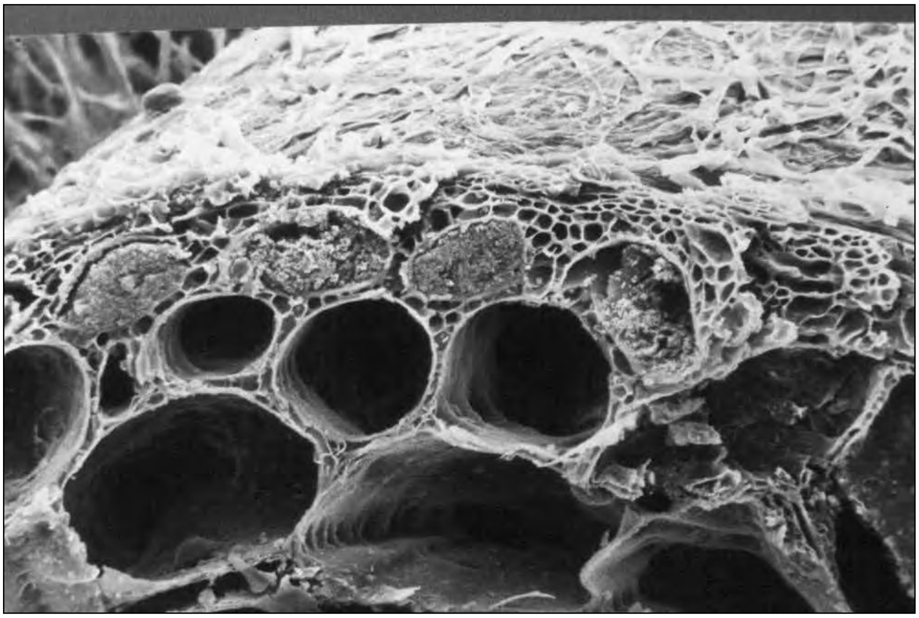
Figure 3



Root cross-section showing mycorrhizal tissue

atmospheric nitrogen N_2 to an organic form that can be utilized by plants, literally generating N fertilizer from "thin air." The beneficial *Rhizobia* bacteria has long been available as an inoculant for legume crops and is usually applied as a liquid or peat-based form to the seed. Nearly 80 percent of Earth's atmosphere is nitrogen, but in spite of it being so plentiful, plants aren't able to utilize it in a gas form. Symbiotic nitrogen-fixing bacteria associated with the roots of legumes are capable of taking substantial quantities of the vast pool of atmospheric nitrogen and converting it to an organic form usable by plants. A good nitrogen-fixing crop can add 200-300 pounds of nitrogen into an acre of soil.

Before the advent of chemical fertilizers, farmers could not maintain high levels of production with the same crops on the same ground year after year. Such practices would produce soils devoid of fertility. In the old days, farmers were careful about rotating crops and incorporating nitrogen-fixing legumes and pulse crops into management practices, which added fertility and organic matter into soils.

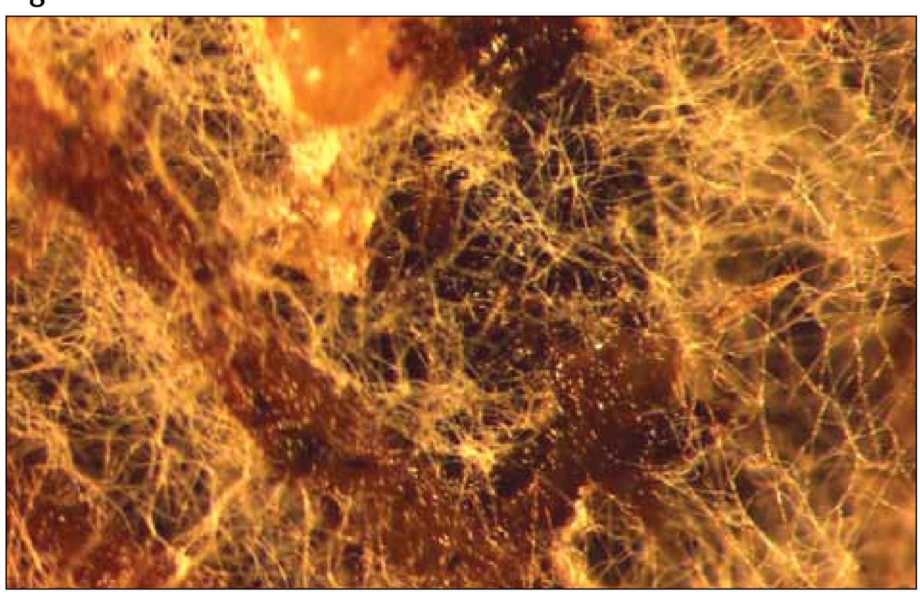
These nitrogen-fixing organisms evolved millions of years ago and helped plants colonize the land. As these early plants gained a foothold on rocky ledges surrounding primordial seas, they helped build soil on the land surface. From ancient times until recent decades, these soil organisms were essential partners in building soil productivity. These organisms are among the most important tools in maintaining the productivity of the farm. The monetary and environmental costs of chemical nitrogen fertilizers are increasingly making biological approaches more attractive to farmers.

Biological nitrogen management aims to provide crops with enough nitrogen at the right time while avoiding resource depletion and nitrogen pollution. Strategies include the use of biological inoculants when growing cover crops and pulse crops such as legumes that utilize nitrogen-fixing *Rhizobia* bacteria to help replenish nitrogen exported at harvest. Similarly, soybeans are inoculated at sowing to optimize the amount of nitrogen fixation within a growing season, capturing additional nitrogen which later becomes available for corn crop rotations.

NINETY PERCENT OF PLANTS DON'T HAVE ROOTS

It might be a revelation to most people that nearly all plants in their natural environments do not have roots. Strictly speaking, they have "mycorrhizae" (pronounced my-cor-rhi-zee) which literally means "fungus-roots" (Figure 3). Yes, 90 percent of the world's plant species form mycorrhizae in their native habitats. This "symbiotic" or mutually beneficial relationship is nothing new. Mycorrhizal fungi, which form the mycorrhizal relationship with plant roots, have co-evolved with plants and soils for more than 460 million years. In undisturbed natural habitats these mycorrhizal fungi proliferate on the roots of plants and spread into the surrounding soil as a great mass of tiny absorptive threads. Plants use their photosynthetic leaves to fulfill mycorrhizal fungal carbon needs while mycorrhizal fungi return the favor by attaining nutrients and water for the plant.

Figure 4

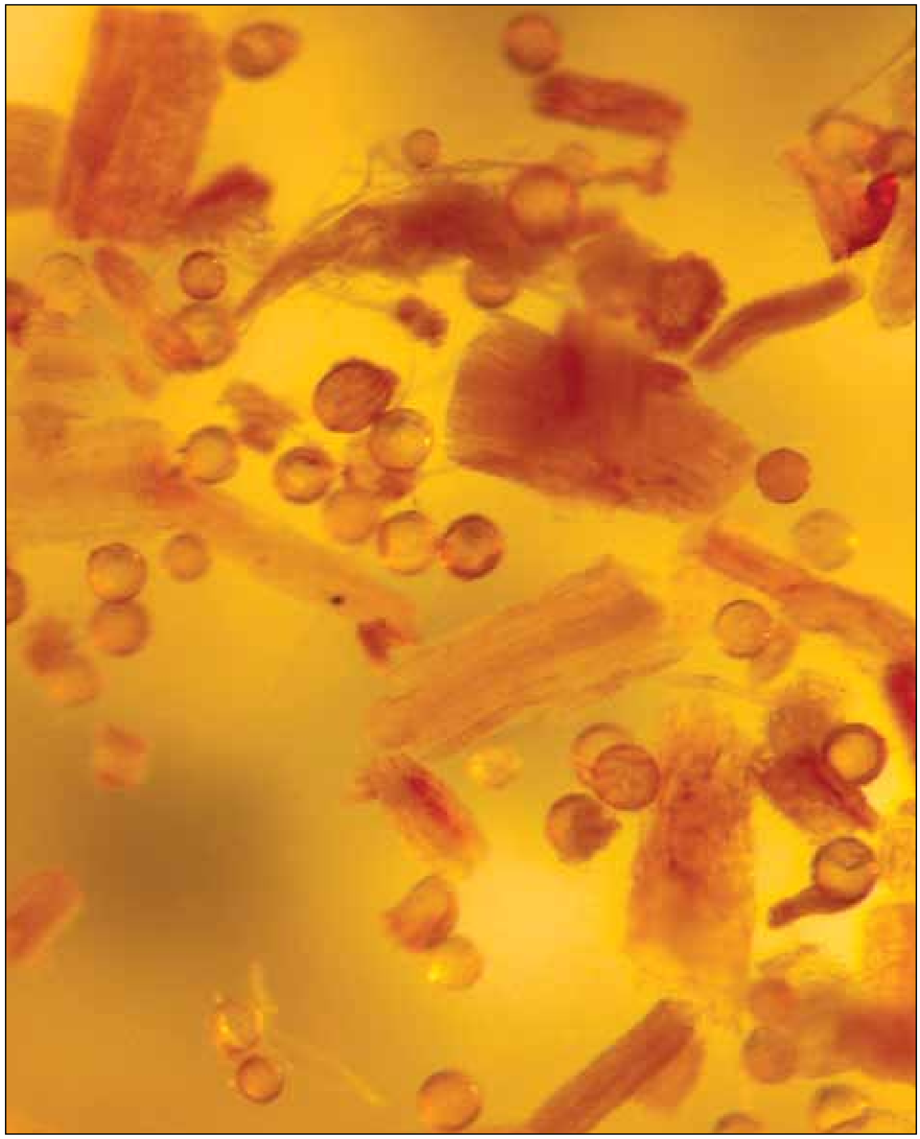


Mycorrhizal hyphae

Mycorrhizal fungi are a big reason why the natural habitats are healthy and productive without artificial inputs of fertilizers and irrigation. Why is this important to farmers? Cropping systems could be more sustainable by managing mycorrhizal fungi for increased yields and greater efficiencies. Hundreds of scientific papers and independent field tests have demonstrated the value of the soil's mycorrhizal fungi. Mycorrhizae increase a plant's uptake of water and nutrients through tiny filaments that extend far beyond a plant's roots. In a single gram of soil, you can find as much as 50 meters of these "hyphae" that transport water and nutrients (Figure 4). The mycorrhizal filaments function like a stomach for the host plant. They dissolve and absorb mineral nutrients in the soil to feed the plants. In the process, they significantly increase crop yields, as well as prevent soil erosion, sequester carbon and provide numerous other benefits.

The mycorrhizal fungi that "digest" nutrients for the plant are as common to plant roots in natural areas as chloroplasts are to the leaves of plants. If you remember your school biology class, chloroplasts capture the sun's light energy during photosynthesis and store it while freeing oxygen from water. So, coming back to basics, chloroplasts, and microorganisms like mycorrhizal fungi in the soil, are true value creators. We need to get to know them better. Our ignorance of the critical role of soil microorganisms has given the Earth a big stomachache. Yogurt is now popular in developed countries to replenish the fauna and flora in our own digestive tracts. Similarly, we can add mycorrhizal inoculum to the soil, as a "probiotic" to restore the digestive health of plants.

Figure 5



Spores and root fragments as propagules

Take the example of a major global crop — soybeans. The fastest, most effective way to restore depleted mycorrhizal populations in soybean acres is to apply a commercial mycorrhizal inoculant to the seeds when planting. Benefits are maximized when the mycorrhizal fungus colonizes the roots as early in the plant's life as possible so seed treatment or in-furrow applications are best. Under ideal circumstances, this occurs immediately after the seed has germinated. The active components in the inoculum are mycorrhizal fungi propagules in the form of spores and colonized root fragments (Figure 5). When one of these colonizing units touches or comes into very close proximity with living root tissue — in this case the sprouted seed — they are activated by minute amounts of specialized root exudates and begin the mycorrhizal colonization process. Soon, the newly colonized root cells begin to send out tiny filaments from the young plant's roots. These filaments then begin absorbing and transporting moisture and nutrients from the surrounding soil, delivering them back to the roots of the host crop. This absorptive web also helps prevent soluble nutrients from leaching into groundwater, nearby streams, lakes or other aquatic environments.

There are increasingly strong incentives to reduce fertilizer use, which continues to increase significantly in cost. For example, the world's remaining phosphorus ore deposits that can be economically mined and processed into fertilizers are limited and will eventually face depletion. Therefore, future increases in food production must be achieved without corresponding boosts in fertilizer use.

In typical conventional farming, more than 50 percent of the fertilizer applied to crops is routinely lost each year, never reaching the plant. Yet that "lost" portion impacts our water and air. Field tests with soybeans, corn and other crops show major efficiency improvements in the uptake of fertilizer and plant nutrition using mycorrhizal inoculation. In a recent three-year test with potatoes, inoculation with mycorrhizal fungi produced significant yield and revenue

Figure 6

Inoculated soybean crop in back compared to control in foreground.

increases when applying just half the amount of phosphorus fertilizer used in conventional practice — 60 pounds per acre instead of 120.

Mycorrhizal inoculation allows reduced total fertilizer inputs because the increased root mass will capture more of the applied fertilizer and, in the case of phosphorus, before it becomes insoluble or, in the case of nitrogen, before it volatizes and/or leaches into the water table as nitrous acid. Mycorrhizal fungi also produce special enzymes that improve the plant's access to other important soil nutrients such as iron, calcium, magnesium, zinc and organic forms of nitrogen.

World demand for food is expected to increase 70 to 80 percent by 2050 and human population is predicted to exceed 9 billion. As the middle class in developing nations grows, the desire for higher forms of protein will likely increase as well, further increasing demands on the soil. For example, meat production is expected to double by 2050; one pound of beef requires 5-10 pounds of feed corn.

BIG SAVINGS USING TINY ORGANISMS

Widespread application of mycorrhizal fungi can increase profits from increased crop yields and immediately produce cost savings on fertilizer and water. In the case of soybeans, independent field studies show that inoculation with mycorrhizal fungi can produce yield increases of 5-20 percent. At current market prices, such yield improvements represent additional revenues three to five times greater than the cost of applying the inoculum. In a market with an annual value of $43 billion, this translates into extra profits of up to $7-8 billion for U.S. soybean farmers (Figure 6). On top of that, the application of mycorrhizal fungi is compatible with conventional soybean growing methods and requires no major new capital investment.

Besides improved yields, further savings can be realized by reducing inputs: the main fertilizer required in soybean production, phosphorus, can be cut dramatically. The conventional strategy is

Figure 7

Corn ears with and without mycorrhizal inoculum during drought. Inoculated on far left and right.

to oversupply soybean crops with phosphorus. The actual uptake is, at best, usually around 20 percent. Much of the remaining phosphorus, even though much stays in the soil, becomes chemically insoluble and unavailable to the crop. But with mycorrhizal inoculation, the more efficient uptake can significantly increase the amount of phosphorus fertilizer actually utilized by the crop. There are hundreds of studies showing the increased efficiency in the uptake of phosphorus in a wide range of crops inoculated with mycorrhizal fungi. The exact improvement will vary depending upon crop, soil chemistry, climate and agronomic practices. Furthermore, mycorrhizal fungi produce enzymes that allow them to reverse the chemical bonds tying up the phosphorus that has become unavailable to the plant.

With regard to cost savings in water, numerous scientific studies have for decades shown that mycorrhizae increase the efficiency of water uptake for plants and increase their drought tolerance, which is key in an age of climate instability. Farmers across the globe will have to switch to cultivating more climate-hardy crops and farming practices. Mycorrhizal fungi give a hundred-fold increase in absorptive area of roots to extract moisture and keep plants growing, often enabling them to forestall stress until the next rain. During the Midwest drought of 2012, a farmer in Iowa inoculated a portion of his crop with mycorrhizae. The inoculated corn produced 190 bushels of corn per acre, while the corn without mycorrhizae produced just 70 bushels (Figure 7). In a wet year the yield difference would be less, but mycorrhizal fungi can help prevent catastrophic loss in dry years. Mycorrhizal fungi can act as a kind of drought insurance as farmers struggle with the effects of a less predictable, changing climate.

THE ORGANIC GLUE

Mycorrhizal fungi contribute yet another great value that growers do not typically calculate in the annual P&L (though that is changing): carbon sequestration. Mycorrhizal fungi have been sequestering carbon for hundreds of millions of years. It has been recently discovered that the hyphal filaments are coated with a sticky glycol-protein called glomalin, and up to 30-40 percent of the glomalin molecule is carbon. The Earth's soil contains more carbon than all plants and the atmosphere combined and it has been calculated that glomalin may account for as much as one-third of that total! A recent study found that, contrary to popular belief, most of the carbon that is sequestered in the northern boreal forests in Canada and in Russia (called the "taiga") derives from mycorrhizal fungi rather than from organic debris such as decaying wood, needles, moss and leaf matter. Most fungal species act as decomposers, eliciting a net release of CO_2 to the atmosphere but mycorrhizal fungi are a notable exception. They act as a mechanism to rapidly transfer carbon from the air into the soil. Glomalin also functions as a kind of "soil superglue," helping to bind soil particles together into tiny aggregates. These aggregates hold moisture and improve tilth, making soil more loamy, nutrient-rich and less subject to erosion. As old hyphal filaments die their glomalin becomes stored in the soil for many years. Microbiologists are currently working to understand its chemical nature and map its gene sequence.

ON SOLID GROUND

There is no doubt that soil is the foundation of terrestrial life on this planet, and we have now established compelling economic and environmental reasons to replenish this critical resource. To address the food security and climate change crises now facing humanity, clearly this is a direction we must turn. It is time to pursue a concept of human health based on nutrition derived from biologically rich soils, all supported by the same natural systems that have sustained terrestrial life and humankind for millions of years. The next time you eat a carrot, consider for a minute the profoundly complex system it took to grow it: soil, rain, sunshine, air — and microorganisms — and remember that you are standing on the living soil.

Mike Amaranthus has published over 70 research studies on soil biology as a U.S. Department of Agriculture Scientist and at Oregon State University. He received the USDA Highest Honors for Science Achievement. He has been featured in the PBS Documentary "The Web of Life" and The History Channel "Modern Marvels." He is currently chief scientist of Mycorrhizal Applications, Inc.