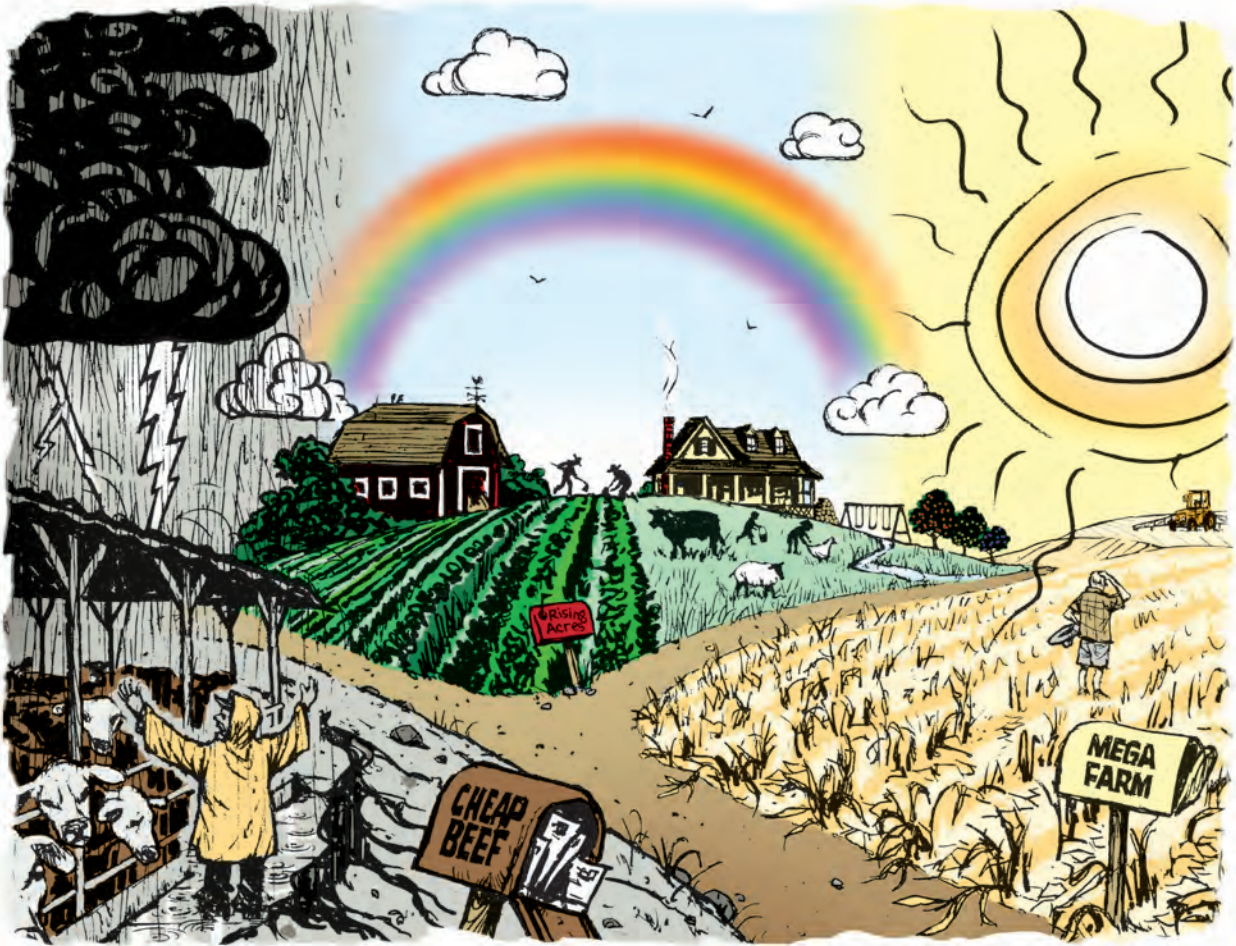


Soil Carbon Restoration: Can Biology do the Job?



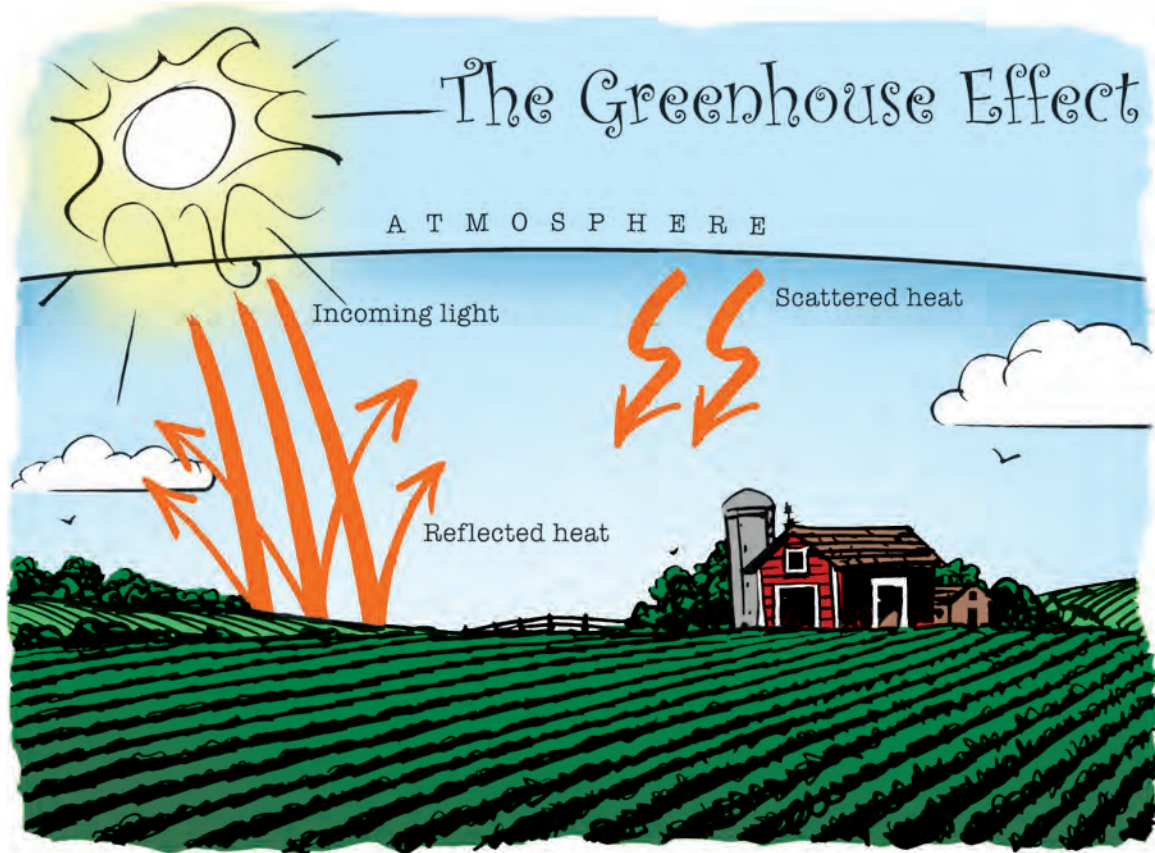
by **Jack Kittredge**,
policy director, NOFA/Mass
www.nofamass.org

Northeast Organic Farming Association/Massachusetts Chapter, Inc.
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Introduction

A great deal of discussion in scientific and governmental circles has been focused recently on how to deal with greenhouse gas emissions and the resulting weather extremes they have created. Most analysts believe we must stop burning fossil fuels to prevent further increases in atmospheric carbon, and find ways to remove carbon already in the air if we want to lessen further weather crises and the associated human tragedies, economic disruption and social conflict that they bring.

But where can we put that carbon once it is removed from the air? There is only one practical approach -- to put it back where it belongs, in the soil. Fortunately, this is not an expensive process. But it does take large numbers of people agreeing to take part. Since few people will change what they are doing without a good reason, we have written this short paper. We hope it explains the problem of carbon dioxide buildup and climate change, how carbon can be taken out of the atmosphere and restored to the soil, and the advantages that can come to farmers and consumers from growing in carbon-rich soils.

Climate Change

Weather anomalies are notoriously difficult to document. To do so requires good data over a long time, and

clear standards for what constitutes an anomaly. Recently, however, as more and more people are interested in the topic, development of the data and standards has progressed. The key factors in extreme weather are excessive heat, precipitation, and air moisture. Recent studies have found that monthly mean temperature records, extreme precipitation events, and average air moisture content have all risen over the last 50 to 150 years. (Coumou)

Most scientists believe that the cause of such unpredictable extremes is the “anthropogenic” (originating in human activities) buildup of greenhouse gases (GHG) in the atmosphere. Rigorous modeling studies and analyses of extreme weather events have found human-caused climate change to be a contributing factor in many such extremes. (Peterson) According to the American Association for the Advancement of Science, “Based on well-established evidence, about 97% of climate scientists have concluded that human-caused climate change is happening.” (AAAS)

How Greenhouse Gases Cause Climate Change

Greenhouse gases, primarily carbon dioxide but also methane, ozone and nitrous oxide, have for millions of years been emitted from soil and water into the atmosphere by natural processes like animal respiration, swamp out-gassing and releases from nitrogen fixing

bacteria. (EPA) Those gases are also broken down by natural processes and returned to their sources in a continual cycle. As long as the amount of greenhouse gases emitted and the amount returned to sources remain balanced, they will not cause climate change.

We need a certain level of greenhouse gases in the atmosphere. They trap solar radiation so that the earth reflects less of it back into space. This raises the amount of heat driving the planetary forces that cause weather. If we did not have some such gases, earth would be frozen year-round and far too cold for human life. The level of a gas in the atmosphere is measured in units called "parts per million" (ppm). Nitrogen, Oxygen and Argon, the primary gases in our atmosphere, collectively account for 999,000 ppm. Throughout human history the atmospheric level of carbon dioxide has stayed at roughly 280 ppm, or less than 0.03%.

Human Disturbance of the Carbon Cycle

Since the dawn of agriculture some 12,000 years ago, however, human caused deforestation, land clearings and crop tillage have released excess carbon dioxide. Using deep ice core analysis and techniques, scientists have detected early spikes in atmospheric carbon dioxide and methane that actually correspond to agricultural expansion thousands of years ago in Mesopotamia and China. (Amundson)

More recently, since about 1750, with the rapid increase in the burning of fossil fuels and the more recent industrialization of agriculture, the scale and number of human-caused sources of GHG have increased dramatically. With more coming out of the ground now, and less returning to it, the level of carbon dioxide in the air is growing and now stands at 400 ppm.

The Scope of the Problem (for those who like numbers!)

Note: calculations in this field all involve use of the metric system, in which a ton is a metric ton that weighs 1000 kilograms or 2204.6 lbs. A Gigaton (Gt) is a billion metric tons. A hectare is 10,000 square meters or 2.47 acres.

Scientists have estimated that we need to get the atmospheric carbon dioxide level back to about 350 ppm to avoid catastrophic climate change. (NASA) (Many researchers argue that a safer goal is closer to the pre-industrial level estimated at 275 - 280 ppm, but most public debate has settled on the 350 number.) One ppm of carbon dioxide in the atmosphere is equal to about 7.8 Gt of it. A molecule of carbon dioxide is mostly oxygen and the carbon in that molecule is only a little

over a quarter of it (27.3% to be precise). Thus one ppm of atmospheric carbon dioxide contains 2.125 Gt of carbon (for purposes of illustration this is about the size of a cubic kilometer of solid graphite).

So we need to be living with carbon dioxide at or below 350 ppm but it is already 400 and growing. What can we do?

Suppose We Lower Emissions?

There is no question that humanity as a whole needs to stop releasing excessive amounts of greenhouse gases. It is estimated that about two thirds of those emissions are because of our burning of fossil fuels. (Ontl) We need to end our reliance on fossil fuels and develop alternative sources of energy. This is well known by governments. International groups have been established to further this goal. It is likely to be one of the hardest changes to make in human history, but we need to find the policies and mechanisms to make this happen if we want to survive. But that is not our only problem.

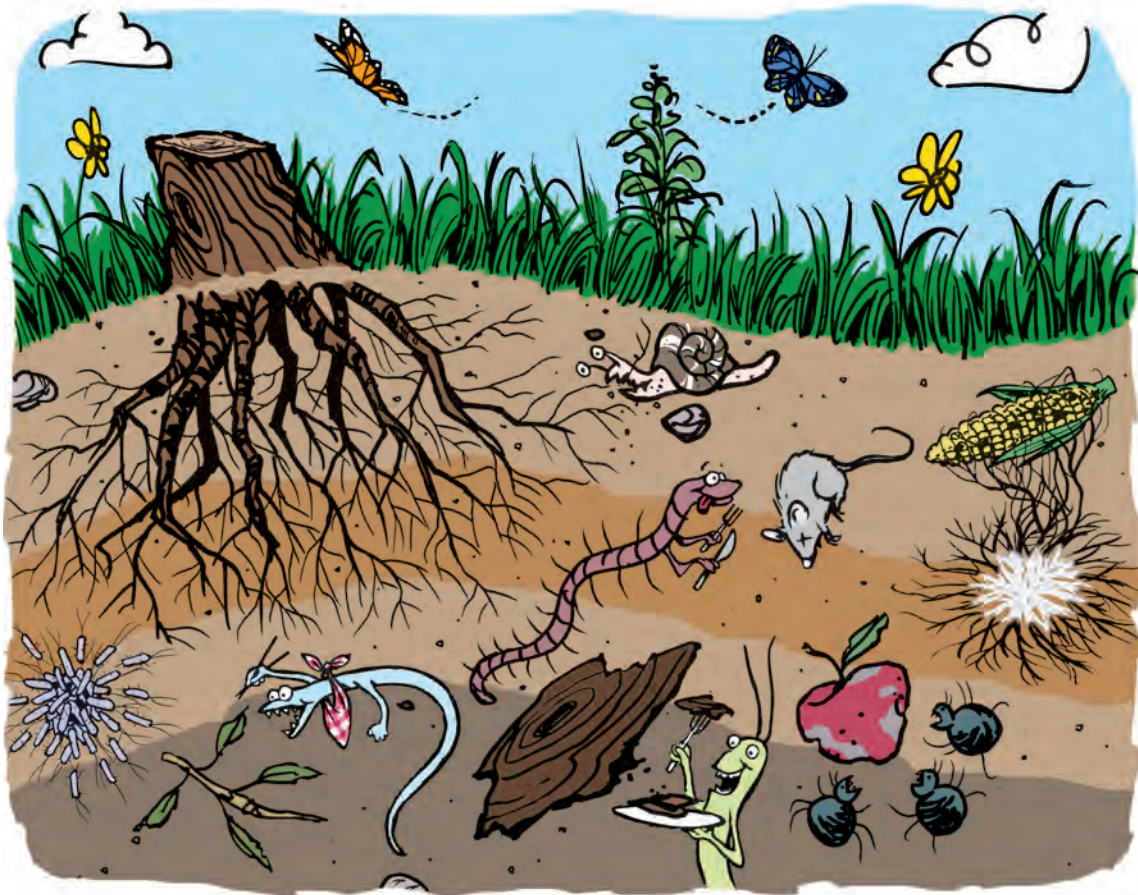
Suppose we could stop all emissions tomorrow? The GHG that we have already released into the atmosphere will continue to heat the globe for decades and perhaps centuries. That heating will melt ice and frozen soils, raising sea levels and releasing large quantities of greenhouse gases still frozen.

This is a potential problem in the arctic, for instance. There an abundance of frozen methane, a potent GHG, can be released into the atmosphere by melting. An enormous amount of carbon is also frozen in permafrost. A warming environment can expose this to digestion by microbes, in which case it will be exhaled as carbon dioxide. If that digestion happens where there is no oxygen, like a swamp or wetland, that carbon will be released by other microbes as methane. (NSIDC)

So lowering emissions is not enough. Once we do that, we must also stop the rise in global temperature. If we are at roughly 400 ppm carbon dioxide now and want to get back to 350 ppm quickly, we need to take carbon out of the atmosphere and bury it somewhere. We need to find a long term home for 50 ppm of carbon dioxide, which is 106.25 Gt of carbon. Can that be done?

Where Can We Put All That Carbon?

We cannot safely store atmospheric carbon in the 70% of the planet that is covered with water. Carbon dioxide dissolves in water and forms carbonic acid. For decades now we have been seeing the effects of a gradually increasing amount of carbonic acid in our oceans. Oceanic pH has been falling and acidification has been



killing many forms of sea life, including shellfish, corals, and plankton. (NOAA)

Storing carbon in the soil, however, is a different story. That is where the carbon came from, and where it is needed. Scientists estimate that since the industrial revolution land clearing and cultivation for agriculture have released 136 Gt of carbon from the world's soil. (Lal 2004) So by our clearing land and tilling fields, soil has lost more carbon than we need to put back. How much carbon does the soil still contain? Vastly more. Again, scientists estimate that in the top 30 centimeters (about a foot) global soils contain around 700 Gt of carbon. If you count the whole top meter of soil (over 3 feet) that number more than doubles to about 1500 Gt. (Powlson) Clearly the soil, which once contained all this carbon, can do so again.

But before we try to answer the question about putting 106.25 Gt of carbon in the soil, let's understand the soil a little better

Soil's Carbon Hunger

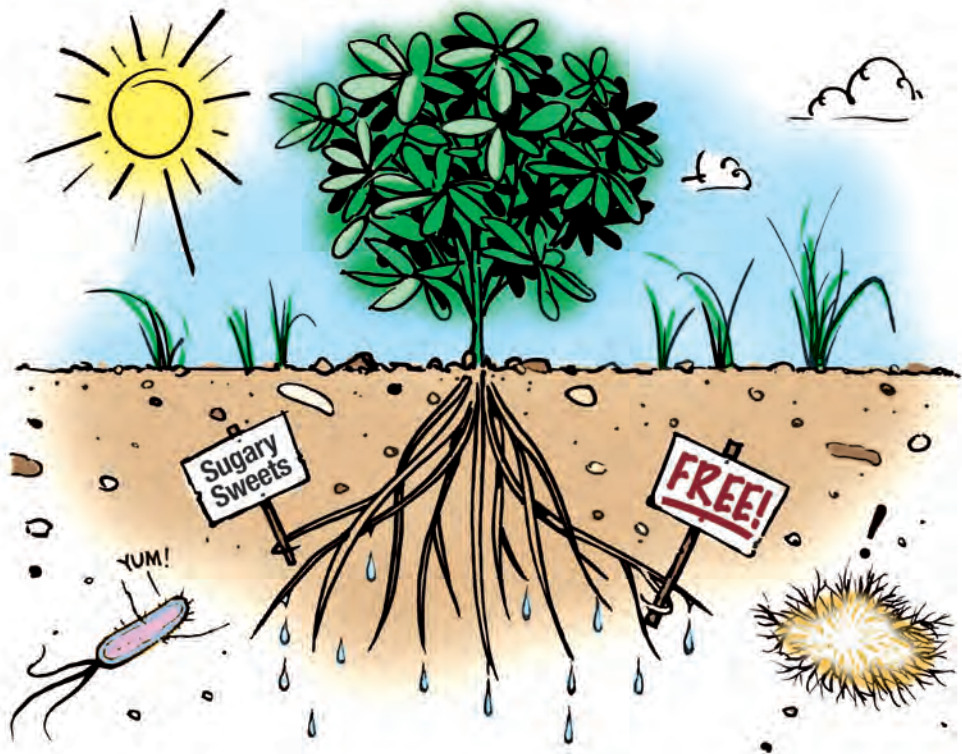
Soil is literally alive. It is full of bacteria, fungi, algae, protozoa, nematodes and many, many other creatures. In a teaspoon of healthy soil, in fact, there are more microbes than there are people on earth. (Hoorman) Of

course, as carbon-based life forms, this teeming community requires constant supplies of organic matter to survive. That organic matter (about 58% of which is carbon) comes in the form of living organisms, their exudates, which are often simple sugars, and their residues, often carbohydrates like cellulose. These compounds are rich in energy, readily accessible to organisms, and rapidly assimilated by soil microbes. The half-life of simple sugars in surface soils, for instance, before they are consumed, can be less than 1 hour. (Dungait)

This tremendous appetite of soil organisms for carbon means that in healthy soil they quickly consume available organic matter. It is taken up into their bodies, or is burned as energy and carbon dioxide is given off. Microbes in an acre of Iowa corn in fact exhale more carbon dioxide than do 25 healthy men at work. (Albrecht) Once those microbes die the carbon in their bodies becomes available for other organisms to decompose and exhale.

The activity of soil organisms follows seasonal as well as daily cycles. Not all organisms are active at the same time. At any moment in time most are barely active or are even dormant. Availability of food is an important factor that influences the population and level of activity of soil organisms. (FAO)

Root Exudates



Photosynthesis

But if carbon is so rapidly consumed in soil, then why does it not quickly vanish?

The answer is that plants are constantly renewing the supply. Since their evolution 3.5 billion years ago, plants have thrived using their remarkable power to take carbon out of the air and put it into living matter. The process, of course, is called photosynthesis, which is taught to most school children.

It works like this: the chlorophyll molecule in plants' leaves allows them to absorb the energy from light and use that to break apart water molecules (H_2O) into hydrogen and oxygen atoms. The plant then releases those oxygen atoms as molecular oxygen (two oxygen atoms bound together – O_2) back into the atmosphere and temporarily stores the hydrogen atoms. In the second stage of photosynthesis the hydrogen atoms are bound to carbon dioxide molecules (CO_2) to create simple carbohydrates such as the sugar glucose ($C_6H_{12}O_6$).

This process, like all chemical reactions, is subject to the availability of the components. Since carbon dioxide is present in the atmosphere at such a low concentration (now 0.04%) it often is the limiting factor in this process. (RSC) At higher concentrations of the gas, more energy will be drawn from available light and more water taken in by the plant to increase carbohy-

drate production. (Ontl) In other situations, like at night or in a drought, light or water can be the limiting factor.

The sheer scale of this process is impressive. An acre of wheat in a year can take in 8,900 pounds of carbon in the form of carbon dioxide, combine it with water, and make it into sugar. The resultant sugar will weigh 22,000 pounds. This process is so active that an estimated 15% of all the carbon dioxide in the world's atmosphere moves through photosynthetic organisms each year. (SAPS)

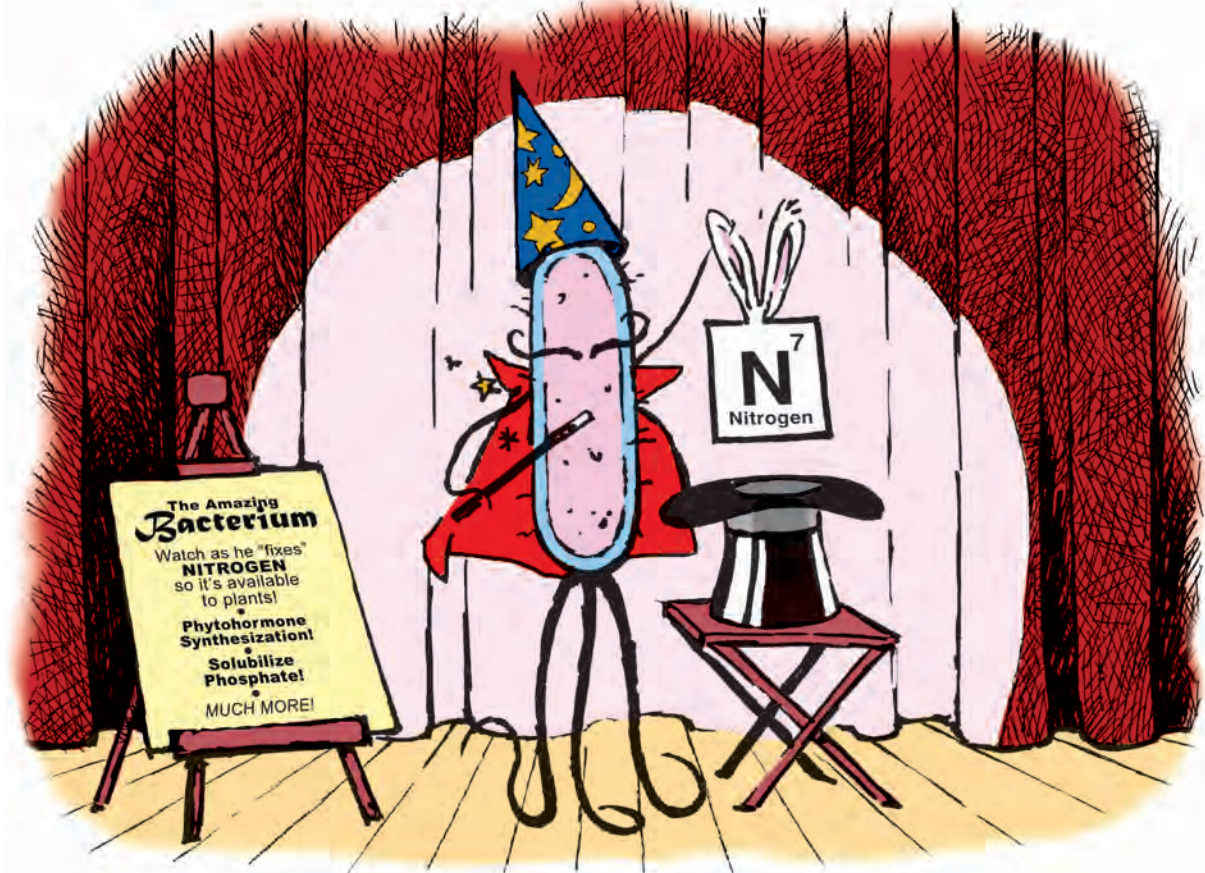
Root Exudates

Photosynthesis, of course, gives plants and other photosynthetic organisms (like blue-green algae) a special role in life. All living things are carbon-based, and need to consume carbon to survive. If you can draw carbon out of thin air, as plants do, you have a commanding advantage. But even if you can't make carbon compounds, you must have them.

How else can soil microbes get carbon? They can "earn" it!

One of the more remarkable things that soil scientists are learning about plants and soil organisms is that they seem to have co-evolved in a mutually beneficial relationship.

The Magician



When plants photosynthesize and make carbohydrates in their chloroplasts, they use some of those compounds for their cells and structure, and some they burn for their life energy. But they “leak” or exude a significant amount of these compounds as “liquid carbon” into the soil. (Jones SOS) Estimates vary but between 20 and 40 percent of the carbon a plant has fixed by photosynthesis is transferred to the rhizosphere (soil zone immediately surrounding the roots). (Walker)

Why in the world would a plant leak sugary sap into the dirt?

As bait.

Hungry bacteria, fungi, and other soil organisms will quickly show up to devour the tasty carbon-containing root exudates. But they soon want more – and the best way to get them is to assist the plant in making more. If a plant is healthy and strong, it can devote more resources to photosynthesis and exude more carbon. So microbes aid the plant in many diverse ways in order to help it thrive and produce more liquid carbon.

As we have learned more about soil biochemistry we have discovered that, through root exudates, plants

have the capacity to control much of their local environment – to regulate the local soil microbial community, to cope with herbivore predation, to “purchase” shipments of distant nutrients, to alter the chemical and physical properties of nearby soil, and to inhibit the growth of competing plants.

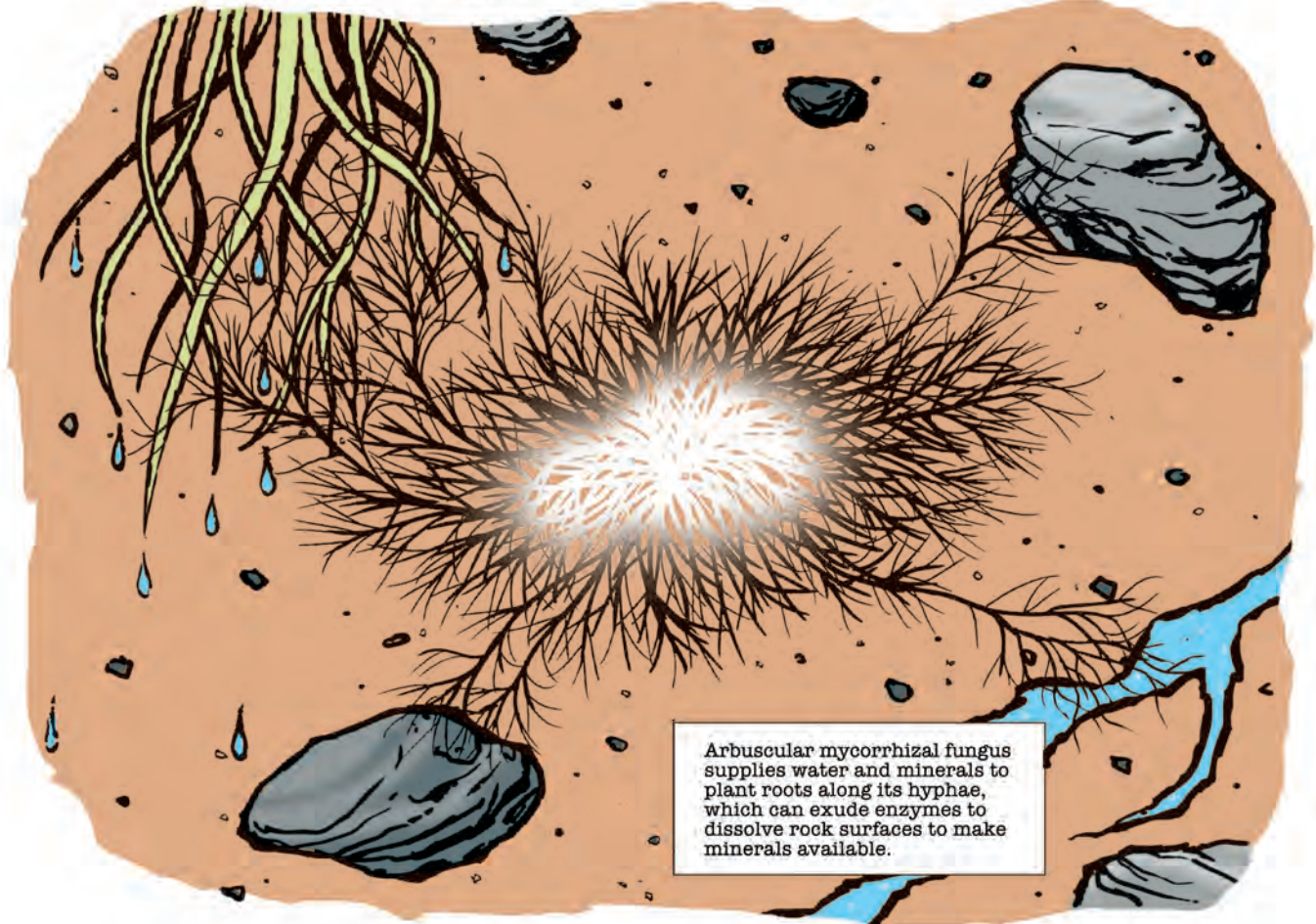
Microbial Symbiosis

It should be stated that much of what follows is still under study. Soils are a frontier about which many things are yet to be learned. The microbial community is extremely diverse -- between 90 and 99% of the species in it cannot even be cultured in labs with current technologies. (Jastrow)

The soil microbial community is more than 90% bacteria and fungi, by mass. The exact ratio between these two kinds of organisms varies. Undisturbed soils like grasslands and forests will benefit fungi whose thread-like hyphae remain undisturbed. Cultivation or the use of synthetic nitrogen fertilizers, however, reduces the fungal population.

A major factor in microbial success is whether or not their immediate physical environment protects them.

Reaching Out



Arbuscular mycorrhizal fungus supplies water and minerals to plant roots along its hyphae, which can exude enzymes to dissolve rock surfaces to make minerals available.

Protection can be provided by clays, which scientists think might maintain an optimal pH, absorb harmful metabolites and/or prevent desiccation. Small pores (for “hiding”) in the local substrate are also thought to prevent predation on the smaller organisms by larger ones like protozoa. (Six) Protected organisms have been reported to die off at a rate of less than 1% a day, whereas as many as 70% of unprotected ones can succumb daily.

Bacteria

Bacteria are amazing chemists. A group of them, called plant growth-promoting rhizobacteria (PGPR), work their magic helping plants through a number of biochemical pathways. Some may “fix” nitrogen from the atmosphere, putting it into a form that is available to plants. Others can synthesize phytohormones that improve stages of plant growth. Yet others can solubilize phosphate, a relatively insoluble essential nutrient, and make it available for plant growth, or produce natural fungicides to assist plants in resisting fungal diseases. (Velivelli) One PGPR has been isolated from many common plants including wheat, white clover

and garlic. This bacterium actually produces different antibiotics, substances that fight pathogens and help plants resist disease. (Timmusk)

Fungi

Another example of microbial symbiosis is that of arbuscular mycorrhizal fungi. In this symbiosis the fungus colonizes two different environments, the roots of the host plant and the surrounding soil, connecting the two with its long hyphae. This enables the host plant to have an improved uptake of water and mineral nutrients conducted along those hyphae. This relationship has been documented in connection with many minerals, including phosphorus, nitrogen, zinc and copper. (Jansa) By some estimates over 90% of terrestrial plants enjoy this association with arbuscular mycorrhizal fungi. (Cairney)

Some scientists estimate that 85 to 90 percent of the nutrients plants require are acquired by carbon exchange where root exudates provide microbial energy in exchange for minerals or trace elements otherwise unavailable to the plant. (Jones SOS)

These relationships benefit both parties, at no cost. The only extra energy needed is provided by the sunlight, which enables the now stronger plant to produce more compounds to energize and support the microbes.

Soil Aggregates

One important aspect of this story is the soil structure called an “aggregate”. If you squeeze a handful of healthy soil and then release it, it should look like a bunch of peas. Those are the aggregates. If the soil remains in hard chunks, then it is not well aggregated. Aggregates are stable enough to resist wind and water erosion, but porous enough to let air, water, and roots move through them.

Aggregates are the fundamental unit of soil function and play a role similar to that of root nodules in legumes, creating a protected space. (Jones SOS) The aggregate is helped to form by hyphae of mycorrhizal fungi that create a “sticky-string bag” that envelops and entangles soil particles. (Jastrow) Liquid carbon exudates from plant roots and fungi enable the production of glues and gums to form the aggregate walls. (Jones SOS)

Inside those walls a lot of biological activity takes place, again fueled by the carbon exudates. Most aggregates are connected to plant roots, often fine feeder roots, or to mycorrhizal fungal networks too small to be seen. The moisture content inside an aggregate is higher than outside, and there is lower oxygen pressure inside. These are important properties enabling nitrogen-fixation and other biochemical activities to take place. (Jones SOS)

One of the important glues which holds aggregates together is a glycoprotein called “glomalin”. Glomalin and soil aggregate stability seem to be closely associated. (Nichols) Just discovered in 1996, glomalin is now believed by some scientists to account for 27 percent of the carbon in soil and to last for more than 40 years, depending on conditions. Glomalin appears to be produced by arbuscular mycorrhizal fungi using liquid carbon exuded by plants. It may enable fungal hyphae to bind to root and soil particles, and to bridge over air spaces. (Comis)

Now that we know more about soil, and how carbon is pumped into it by plants to encourage symbiotic relationships with microbes, we can ask the question again:

How Quickly Can We Restore Enough Carbon to the Soil to Mitigate Weather Extremes

We have seen above that one part per million of carbon

dioxide in the atmosphere contains 2.125 Gigatons of carbon. If that is the case, and we are at 400 ppm and need to get back to 350, we need to restore 50 ppm, or 106.25 Gt of carbon, to the soil.

We know that all that carbon will fit in the soil because that is where it came from. We have brought 136 Gt of carbon out from the soil by land clearing and agriculture since the beginning of the industrial age.

But how quickly can we put that carbon back in? Over the last 20 years, since people have been thinking about restoring carbon in soil, many studies have been done to measure the rate at which agricultural photosynthesis can build up soil carbon. We have looked at a number of those studies, conducted over the last decade or so, covering many different types of soils on five continents and various kinds of agriculture. The studies use different methodologies and of course report quite divergent results. But from reading those studies, several things are evident.

- Perennial growing systems can restore more carbon than most other agricultural methods. All the pasture based trials reported exceptional amounts of carbon restored, from 1.9 to 3.2 metric tons of carbon per acre annually, and averaging 2.6 tons. (Machmuller, Rodale, IFOAM) We have found few studies of perennial cropping systems building large amounts of soil carbon, but there is some evidence that perennial woody crops can do so. One study found that degraded mining soils gained 2.8 metric tons of carbon per acre per year when planted to the legume black locust and managed as a coppiced biomass crop in a short rotation system. (Quinkenstein) More studies need to be done before we can fully evaluate the contributions of perennial woody or herbaceous crops to restoring soil carbon.

- Use of synthetic chemical fertilizers, especially nitrogen and phosphorus, will seriously reduce or in many cases even eliminate any soil carbon buildup. The appropriate use of manure and compost, however, does not seem to impede soil carbon increase. (Jones SOS, Rodale)

- Studies of row crops, even when raised without synthetic chemicals, reported carbon gains smaller than did pasture studies, ranging from 0.23 to 1.66 tons per acre, with an average of 0.55 tons. (Khorramdel, IFOAM)

- The quality of the farming practices studied was variable, especially for the row crop trials. Virtually all the row crop studies reporting significant gains were those using manure or compost instead of chemical

fertilizers. But the extent to which other principles of carbon building -- such as keeping the soil covered with plants at all times, using a broad mix of cover crops, and minimizing tillage -- were used is not clear. It is noteworthy, however, that in the case of the highest reported row crop carbon gain, restoring 1.66 tons per acre of corn, the trial used organic no-till practices. (Khorramdel)

Given these trial averages, let's do some back-of-the-envelope calculations about the potential of agriculture to restore 106.25 Gt of carbon to the soil.

The FAO says there are 8.3 billion acres of grasslands on the globe and 3.8 billion acres of cropland. If everyone were willing to use carbon-building practices on those acres annually the grasslands, at an average of 2.6 tons per acre, could restore 21.6 Gt and the croplands, at an average of 0.55 tons per acre, could restore 2.1 Gt. This gives us a total of 23.7 gigatons per year. Since we are interested in restoring 106.25 Gt, that means we could do it in under 5 years!

Stable Carbon

Of course if we want to restore a large amount of carbon to the soil it has to be done so that microbes can't consume it. Otherwise they will eventually just burn it up and give it off as carbon dioxide to the atmosphere again. Many studies have analyzed treatments for soil organic matter to see if they helped preserve it. One 10-year study compared incorporating organic matter residues in one plot and removing them from a similar plot. Another one lasted for 31 years and compared different rotations and fertilizer applications in different plots, varying by up to 50% the amount of carbon returned to the soil. A third compared a plot where crop residues were burned for many years to another plot where the residues were incorporated into the soil. At the end of each of these studies, researchers measuring soil organic matter could find no significant differences among the plots despite the differences in management. (Kirkby)

If microbes will just multiply and consume whatever carbon is present, we can never build higher levels in the soil. And yet, historically, soil organic matter levels of 6 to 10% were common, and in places as much as 20% was measured. (LaSalle) What has kept soil organisms from decomposing organic matter in the past?

One form of carbon that seems to remain stable for years, even centuries, is humus. It is composed of complex molecules containing carbon, but is not easily broken down by soil life. Scientists are not entirely in agreement on how humus is formed, or how it resists

decomposition. Some believe that humus is a highly recalcitrant form of carbon formed by the microbial decomposition of roots and root products. (Ontl)

Others believe that the mechanisms enabling physical preservation of soil carbon involve either its ability to resist attack by microbial enzymes through "adsorption" onto minerals, or protection within soil aggregates. The former suggests chemical bonding to clay particles or soil colloids strong enough to resist attack by threatening enzymes. The latter might protect the molecules from an enzyme attack by keeping oxygen or other decomposing elements out of the soil aggregate. Still another theory involves the inaccessibility of the soil carbon to microbial attack because of its depth within the soil. (Dungait)

A view is developing among some scientists, however, that stable carbon is produced not from residues of soil organic matter but from liquid carbon itself. This view sees humus as a built-up creation by soil organisms, rather than a product of decomposing organic matter. (Meléndrez, Jones letter)

Studies supporting this view suggest that humus is an organo-mineral complex composed of about 60% carbon, between 6% and 8% nitrogen, and chemically linked to soil minerals including phosphorus, sulfur, iron and aluminum. There is even some evidence that the composition of humus is based on specific ratios among its main components, not only between carbon and nitrogen but also between carbon and sulfur. (Kirkby) One researcher maintains that humus can only form in specialized soil microsites, like aggregates, where nitrogen is being actively fixed and phosphorus and sulfur are being solubilized, (Jones letter)

How Can We Restore and Stabilize Soil Carbon?

As soil scientists learn more about the components and microbial processes that form humus we will have a better understanding of how to assist its creation. But there is evidence suggesting that building soil organic matter is not just a job of adding organic matter to your soil. That will create a thriving microbial community and can make crops flourish. But to build long term carbon, you need to do more.

What we need to know is: what practices do we need to use to build and keep soil carbon in our soil?

Keep Soil Planted

Probably the most important single lesson is that bare soil oxidizes carbon, while plants protect it. Green



plants form a barrier between air and soil, slowing the process of carbon emission by microbes. Erosion by wind and water is also a major enemy of soil carbon, and growing plants are your best protection against erosion. Finally, plants not only protect soil carbon but also add to it through their power of photosynthesis. Put simply, every square foot of soil that is left exposed -- whether it is between rows of crops, because you are tilling up a field, or have just harvested a crop and are leaving the land to fallow -- reduces your carbon bank account.

Practices like winter vegetation to cover the soil and under-sowing with legumes and cover crops are important so that after the crop is taken there is a productive cover to increase soil carbon, protect against erosion, feed soil organisms and increase aggregation. (Azeez)

Minimize Tillage

One of the most difficult carbon restoration practices for organic growers to adopt is to reduce tillage. Since organic growers don't use herbicides, tillage of the soil is their major weapon against weeds. But tillage does several detrimental things. First, it stirs up soil and ex-

poses it to the air, oxidizing the carbon in the exposed soil. Second, tillage rips up and destroys the hyphae of mycorrhizal fungi, the microbes responsible for much of the symbiosis that is so important for plant vigor and increased exudation of liquid carbon. Their hyphae are the delicate network strands that permeate the soil and carry water and nutrients to plant roots. Studies report increases in fungal biomass at all sites where tillage is reduced. (Six) Third, the complex soil aggregates that have been built up of microbial exudates to protect important chemical transformations such as nitrogen fixing and carbon stabilization will be ruined by tillage. Fourth, tillage tends to destroy the pore spaces in the soil that are vital for holding air and water, which enable microbial vitality. Finally, tillage itself often involves equipment that is powered by fossil fuels, releasing greenhouse gases in their operation.

Studies report that the organic cropping systems with the highest levels of carbon restoration are those practicing no-till and adding plenty of organic matter -- such as cow manure -- to the soil. (Khorramdel) Critics of tillage report that even one tillage operation after several years can result in loss of most of the carbon built up during that time. (Lal 2007)

There are some studies that report that the soil carbon gains of no-till are not distributed deeply through the soil profile, but rather occur mostly near the surface. This is a problem, they suggest, because the best chance for humus formation and long-term carbon stabilization seems to be deeper in the soil, closer to clay and minerals to which the carbon can bond to resist oxidation. They also argue that the kind of soil organic matter produced under no-till management is only incorporated in the sand/soil fraction of the soil near the surface and is easily oxidized upon eventual disturbance. (Azeez)

Some studies that point to the shallowness of organic matter build-up under no-till, however, also report a slow deepening of soil organic matter after 10 to 15 years under the system, presumably because of both decreased organic matter decomposition and long term soil mixing by larger soil organisms. (Powlson)

There are several systems and devices that are currently being designed for organic growers to reduce tillage. Planters are available that open the soil only enough for the seed or seedling to be deposited, and close it right up again afterward. Roller-crimpers have been designed which roll over and crimp a long stemmed cover crop before flowering, killing it but not disturbing the soil. The market crop is then planted right into the stubble of the cover. Doubtless many other good ideas for enabling organic farmers to fight weeds while not disturbing the soil will be developed. There is certainly a need for more progress on this front.

An alternative method of controlling weeds is the use of mulch to prevent light from reaching them. The simplest mulches to apply are sheets of plastic. Their production, however, usually requires fossil fuels and removal can be difficult and time consuming. Mulching with organic materials such as hay or shredded crop residue adds decomposing organic matter to the soil and builds carbon, but in biologically active soils requires continual additions of material which can be costly and time-consuming. The primary drawback to mulching, however, is that it does not take carbon from the atmosphere and fix it into the soil via photosynthesis, as living plants do.

Cover Crops

Cover crops are essential in any organic strategy to reduce or eliminate tillage, control weeds, and build soil carbon. Ideal candidates for cover crops can be killed (by frost, mowing, crushing) before flowering, so they

don't produce seeds and become weeds themselves. Their photosynthesis is an important source of soil carbon while living, and their biomass becomes available after they die. Legumes are important in the cover crop mix, as are deep-rooted plants like annual ryegrass or cereal rye that bring nutrients from deep in the soil and add nitrogen and carbon back to those lower levels.

Besides increasing soil carbon, cover crops reduce nitrogen leaching and discourage wind and water erosion. They improve soil structure, increase water infiltration and reduce evaporation. They also provide higher levels of lignin than most cultivated crops, thus supporting mycorrhizal fungal growth and fungal products such as glomalin that promote soil particle binding. (Rodale, Azeez)

Diversity and Crop Rotation

One of the keys to supporting the microbial life in the soil is to encourage diversity. One principle of nature seems to be that the more biodiversity there is in a system, the healthier and more resilient it is. This is also true when building soil carbon. (Lal 2004) Below ground, biodiversity enables every microbe to fill a niche in the food web – fungi, algae, bacteria, earthworms, termites, ants, nematodes, dung beetles, etc. Above ground, monocultures invite pests and disease where crop diversity keeps infestations from growing and spreading. This applies to both crops and to cover crops, which should contain many plants of different types – broad leaf and grass, legumes and non-legumes, cool and warm weather, wet and dry. No matter what the conditions, some should be able to thrive and photosynthesize. “Cocktail cover crops” are mixes of many varieties of cover crop seed and are now available for purchase to guarantee biodiversity.

Crop rotations also help benefit biodiversity. Rotations with continuous cover crops eliminate the need for fallow periods to refresh the land and increase the activity of soil enzymes. Microbial biomass is larger when legumes are included in the rotation. (Six)

Grazing ruminants are also a common way for organic farms to improve soil organic matter levels. The grazing itself promotes the growth, then sloughing off, of grass roots -- which provides carbon to feed hungry soil microbes. Pastures and perennial systems, if properly managed, can show rapid increases in organic matter. Animal manure is one of the most valuable products of the small mixed farm, rich as it is in both carbon and the living microbes that inoculate soil with biological diversity.



No Chemicals

The use of synthetic agricultural chemicals is destructive of soil carbon. Toxins like pesticides are lethal to soil organisms, which play a crucial role in enhancing plant vitality and photosynthesis. Fertilizers have also been shown to deplete soil organic matter. In the Rodale Institute's Compost Utilization Trials using composted manure with crop rotations for ten years resulted in carbon gains of up to 1.0 ton/acre/year. The use of synthetic fertilizers without rotations, however, resulted in carbon losses of 0.15 ton/acre/year. (LaSalle)

The Morrow Plots at the University of Illinois were the site of one of the longest running controlled farm trials in history. Researchers analyzed data from 50 years in which fields on which a total of from 90 to 124 tons of carbon residue per acre had been added, but which also used synthetic nitrogen fertilization. Those plots actually lost almost 5 tons of soil organic matter per acre over the trial period. (Khan)

One suggested cause of the negative impact of synthetic fertilizer on soil carbon is the fact that it tends to reduce the size and depth of plant roots since it is concentrated in a shallow layer at the soil surface rather

than spread throughout the soil as would be nutrients from legumes, minerals or other natural sources. (Azeez) Another reason might be the impact on the plant of absorbing ammonium ions which causes it to release hydrogen ions, which acidify the soil. (Hepperly) A third possibility is that the availability of free nitrogen causes the plant to exude less liquid carbon to obtain nitrogen from microbes. If you have been using synthetic nitrogen fertilizers, however, and want to stop doing so it may be wise to cut back gradually over three or four years because it will take time for nitrogen-fixing bacteria to build up in your soil. Stopping cold turkey may result in disappointing yields the first year. (Jones SOS)

Pasture

We have noted earlier that proper pasturing is a highly effective method of agriculture to restore soil carbon. A recent study of land converted from row cropping to management intensive grazing showed a remarkable carbon accumulation of 3.24 tons/acre/year. This is in the range of deep-rooted African grasses planted to savannas in South America that achieved rates of 2.87 tons of carbon/acre/year. (Machmuller)

Part of the efficiency of pastures at fixing carbon is probably related to the fact that several grasses use the C_4 photosynthetic chemical pathway, which evolved separately from the more usual C_3 pathway. Particularly adapted to situations of low water, high light and high temperature, C_4 photosynthesis is responsible for some 25 to 30% of all carbon fixation on land, despite being used by only 3% of the flowering plants. (Muller)

Some people are concerned about raising large numbers of ruminant animals because in the process of digestion they employ bacteria in their rumen that give off methane, a greenhouse gas that the animal then exhales. In an ecological setting this is no problem as methanotrophic bacteria, which live in a wide variety of habitats and feed solely on methane, will quickly metabolize it. In fact, after the Deepwater Horizon oil spill in the Gulf of Mexico, some 220,000 tons of methane bubbled to the surface but were quickly consumed by an exploding population of methanotrophic bacteria. It is only when ruminants are away from biologically active soil or water, such as in feedlots or on soil to which synthetic chemicals have been heavily applied, that ruminant methane emissions can be of concern. (Jones SOS)

Forests

Converting degraded soils to forest use has been proposed as a way to enhance soil carbon. As with other plants, the rate of forest soil carbon restoration depends on climate, soil type, species and nutrient management. The studies we have found on soil carbon in forests generally show modest gains in soil carbon or, in some cases, a net loss. (Lal 2004) There are some, however, that suggest proper management of woody plants can also deliver sizeable soil carbon gains. (Quinkenstein) Also, reforestation can lead in other ways to climate moderation and water cycle restoration.

Biochar

The potential for use of charred residues to enhance soil fertility while restoring carbon to the soil has recently gained a lot of attention. Pointing to the *terra preta* soils of the Amazon, anthropogenic dark earths enriched with char more than 800 years ago, proponents cite the high fertility these soils have even today. Other char-containing soils are Mollisols, grassland derived soils extensive in North America, the Ukraine, Russia, Argentina and Uruguay that produce a significant portion of global grain harvests. The char in these soils has been attributed to grassland fires that occurred long ago. The actual chemistry of these char residues has only recently been investigated. Their stability and fertility may be related to protective habitats their inter-

nal spaces provide for microbes, or to char's molecular structure, which creates a large cation exchange capacity (ability to hold ions of minerals needed for plant nutrition). (Mao)

Although biochar has not been extensively studied, researchers suggest that biomass carbon converted to biochar can sequester about 50% of its initial carbon in the soil for long periods, leading to a more stable and long-lasting soil carbon than would be the case from direct land application of uncharred carbon. (Dungait)

Of course any conversion of carbon to biochar must involve a life cycle assessment concerning the source of the carbon, its land use implications, and the energy of processing and applying it. There are some indications, however, that biochar is a good way to confer additional stability to labile, or easily broken down, organic matter in soil. (Powlson)

Benefits of Restoring Carbon to Soil

The advantages of building organic matter in your soil are not limited to removing carbon dioxide from the atmosphere.

Water

Increasing soil carbon builds aggregates, which in turn act as sponges to enable soil to hold water, thus providing reserves to plant roots in times when precipitation is low and a ready sink to soak up excess in times when it is high. This capacity to retain water also reduces the risk of erosion and can result in improved crop quality and yield. Some growers believe that companion plants or a cover crop will use up all available water or nutrients. To the contrary, supporting soil microbes with a diversity of plants actually improves the crop's nutrient acquisition and water retention. (Jones SOS)

Interestingly, since the 1930s the mean maximum and minimum water levels of the Mississippi River have gotten more extreme – flood levels are higher and low river levels are lower. This happens because the water cannot infiltrate the soil as it should. With good infiltration some water supplies plant production and some flows slowly through the soil to feed springs and streams which bring a long lasting base flow to river systems. But if groundcover is poor, soil aggregation diminishes and water cannot infiltrate well. Thus in floods water runs along the surface and erodes soils, and in droughts there is no supply retained in the soil for either plants or maintaining flow to springs and streams. (Jones SOS)

Fungal Dominance

Scientists are finding that a high ratio of fungi to bacteria in soil is very important to plant production. You can tell if you have such a ratio by the aroma of a handful of soil – if it is mushroomy, not sour. It is the fungi that seek out and supply water and nutrients to plant roots as needed. Unfortunately, most of our agricultural soils are bacterially dominant, rather than fungally dominant. But practices that avoid bare soil, do not till, use cover crops of many species, and encourage high density but short duration grazing with significant rest periods are moving soil toward fungal dominance.

Better Crops

Plants, just like animals, have evolved complex defenses against enemies. Their mechanisms are many, and clever. Some avoid detection by adopting visual defenses such as mimicking other plants or camouflaging themselves. Some make attack difficult by putting on armor such as thick cell walls, waxy cuticles, or hard bark. Some deter predation by use of thorns, spines, or sticky gum-like exudates. Many synthesize secondary metabolites to prevent attacks chemically (poisons, repellants, irritants, or even volatile organic compounds that attract the enemies of the plant's predator). (Wink) Plants also engage in symbiotic relations with bacteria that are able to inhibit local pathogens and thus defend plants against attack.

Such abilities, just as is the case with immune systems in animals, are strongest when the plant is healthy. That health is optimal when the needs of the plant for sunlight, nutrition, water, oxygen, and carbon dioxide are fully met. And of course that happens best in healthy

soil with a high carbon content and a diverse and large population of microbes. Those conditions can lead to crops with nutrient density, resistance to pests and diseases, more antioxidants and longer shelf life. (Gosling, Wink, Reganold)

Plants that are not held back by disease or predation and have their nutrient needs met are going to thrive and give abundant yields. Also, healthy plants biosynthesize more of the volatile molecules and higher metabolites that produce the flavors and aromas of food crops. So restoring carbon to soils is a way to benefit all: farmers with larger yields, gardeners with tastier crops, and consumers with healthier food.

Conclusion

Using biology to restore organic matter to soils and stabilize it is not only beneficial to those who manage land and crops but is also vital to our society. We have taken too much carbon from the soil, burned it, and sent it into the atmosphere as carbon dioxide. Even were we to stop burning fossil fuels tomorrow, the greenhouse gases already released will continue to raise global temperatures and set free more harmful gases many years into the future.

If we want to survive we really have no alternative but to restore carbon to the soil. That this can be done through biology, using a method that has worked for millions of years, is exciting. Farmers, gardeners, homeowners, landscapers -- anyone who owns or manages land -- can follow these simple principles and not only restore carbon to the soil but help rebuild the marvelous system that nature has put in place to renew our atmosphere while providing food, beauty and health for all creation.

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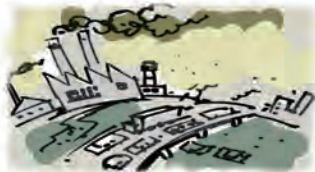
For more information on restoring soil carbon: www.nofamass.org/carbon

How organic farming can save the world!



Our poor Earth.

Day after day, carbon dioxide gas is pumped into the air, warming up our planet and threatening our environment.



Fortunately for us, there's a solution -- and it's right underneath our feet



Organic farming is here to save us! TA-DAH!



Good soil management helps promote the growth of healthy plants that absorb sunlight.



Plants then use their own chlorophyll along with carbon dioxide and water to produce -- carbohydrates!



Some of the sugars in these 'liquid' carbohydrates are 'leaked' or exuded down through the roots and, like magic, attract hungry microbes in the ground -- like bacteria and fungi.



Together, green plants and organisms in the ground protect and promote each other's health.



Best of all, this process locks the carbon into organic matter, can create humus in the soil (learn how in this paper) and...



...that keeps our planet healthy!



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