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Soil Carbon Restoration: Can Biology do the Job? Part Two

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Key Points

- Through photosynthesis plants can draw carbon, in the form of carbon dioxide, out of the atmosphere and put it into living matter, constantly renewing the supply in soil.
- Soil scientists are learning that plants and soil organisms seem to have co-evolved in a mutually beneficial relationship.
- Research on the capacity of agricultural lands to hold increased amounts of carbon is incomplete.
- If we are to restore a large amount of carbon to the soil it must be done so that microbes cannot consume it. Otherwise, they will eventually just burn it up and give it off as carbon dioxide to the atmosphere.
- 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 organisms in the soil.

Summary

In the second part of his paper, Jack Kittredge firstly provides a succinct description of the photosynthesis process as a driver of the carbon cycle. He then provides a description of the components of soil and the interrelatedness of these components. This underpins the complexity of soil as a living substance, teeming with life, particularly microbial life. The question is then asked: how quickly can we restore enough carbon

to the soil to mitigate weather extremes? This leads the discussion to the need for stable soil carbon and to where this stable carbon is likely to be found.

Analysis

Soil 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 per cent 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 one 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)

Photosynthesis

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 ($H20$) into hydrogen and oxygen atoms. The plant then releases those oxygen atoms as molecular oxygen (two oxygen atoms bound together – $O2$) 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 ($CO2$) to create simple carbohydrates such as the sugar glucose ($C6H12O6$).

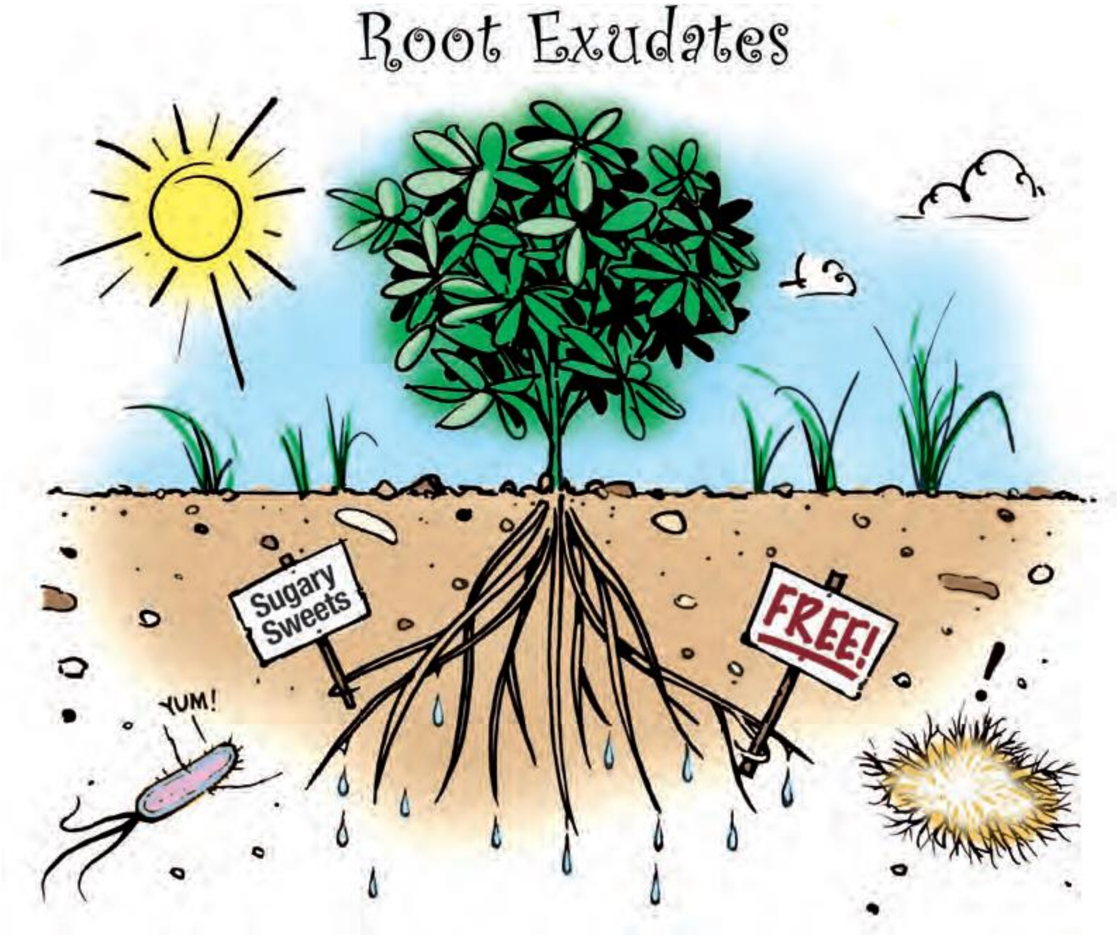
This process, like all chemical reactions, is subject to the availability of the components. Since carbon dioxide is present in the atmosphere at such a low concentration (now 0.04 per cent) it often is the limiting factor in this process. (RSC) At higher concentrations of the gas, more energy will be drawn from available light and more water taken in by the plant to increase carbohydrate 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 4000 kilograms of carbon in the form of carbon dioxide, combine it with water, and make it into sugar. The resultant sugar will weigh

10,000 kilograms. This process is so active that an estimated 15 per cent 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 cannot 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.

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 per cent 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 microorganisms 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. Microbes aid the plant in many diverse ways 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 per cent of the species in it cannot even be cultured in labs with current technologies. (Jastrow)

The soil microbial community is more than 90 per cent 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 their immediate physical environment protects them. 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 one per cent a day, whereas as many as 70 per cent 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 produces different antibiotics, substances that fight pathogens and help plants resist disease.

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 per cent of terrestrial plants enjoy this association with arbuscular mycorrhizal fungi. (Cairney)

Some scientists estimate that 85 to 90 per cent of the nutrients that 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 like 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 fuelled 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.

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. to 3.2 metric tonnes of carbon per acre annually and averaging 2.4 tonnes. (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 tonnes 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 research needs to be done before we can fully evaluate the contribution of perennial woody or herbaceous crops to restoring soil carbon.

The 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 1.5 tonnes per acre, with an average of 0.55 tonnes. (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 always covered with plants, using a broad mix of cover crops, and minimizing tillage, is not clear. It is noteworthy, however, that in the case of the highest reported row crop carbon gain, restoring 1.66 tonnes per acre of corn, the trial used organic no-till practices. (Khorramdel)

Given these trial averages, let us 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 2.5 tonnes per acre, could restore 21.6 Gt and the croplands, at an average of 0.5 tonnes 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 are to restore a large amount of carbon to the soil it must be done so that microbes cannot consume it. Otherwise they will eventually just burn it up and give it off as carbon dioxide to the atmosphere again. Many studies have analysed 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 fertiliser applications in different plots, varying by up to 50 per cent 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 per cent were common and, in places, as much as 20 per cent 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 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 per cent carbon, between 6 and 8 per cent nitrogen, and chemically linked to soil minerals including phosphorus, sulphur, iron and aluminium. 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 sulphur. (Kirkby) One researcher maintains that humus can only form in specialized soil microsites, like aggregates, where nitrogen is being actively fixed and phosphorus and sulphur are being solubilized, (Jones letter).

Conclusion

In Part Three of this paper, Jack Kittredge asks the critical question: how can we restore soil carbon? He then describes, in considerable detail, the procedures and practices that will promote the restoration of carbon to agricultural soils. He also highlights the benefits this provides by promoting healthy and resilient soil. The paper concludes with a clear statement of the importance of restoring carbon to the soil.

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