Putting It Back: Restoring Lost Soil Carbon Could Benefit Agriculture, Ecosystems, and Climate

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Fossil fuels get most of the blame for climate change—and rightly so. Carbon dioxide from the burning of coal, oil, and gas is believed to be the single biggest factor contributing to global warming, but large-scale fossil fuel use has happened only in the industrial era. In contrast, agriculture, which started at the dawn of civilization 10,000 years ago, is estimated to have released even more carbon into the atmosphere, primarily from the soil. Unlike the case with fossil fuels, however, this process could potentially be reversed, putting carbon back in the soil, improving not just the climate outlook, but ecosystems and food security as well. In theory, soils of the world could soak up nearly a third of the carbon added to the atmosphere by humans each year that is not removed by other natural mechanisms. ''That could help us address some of our climate change challenges, at least in the short term,'' says Pete Smith of the University of Aberdeen in Scotland. ''While reducing fossil fuel emissions has to be the bottom line, soil carbon sequestration has a significant mitigation potential we can't dismiss.''

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Globally, soil holds about 2,500 gigatons (Gt) (billion metric tons) of carbon already, although estimates differ. Natural biochemical processes of the carbon cycle circulate vast amounts of carbon between the air, vegetation, and soil each year. Plants take in about 120 Gt of carbon from the air by photosynthesis and respire 60 Gt back into the atmosphere. They deposit 60 Gt of organic debris on the ground, feeding soil microbes that breathe another 60 Gt of carbon back into the atmosphere. Thus, the carbon flowing between air and soil is roughly in balance. Human activities such as fossil fuel burning and deforestation upset this equilibrium by adding more carbon to the atmosphere. Oceans and land vegetation absorb some of these emissions, but an extra 3.5 Gt of carbon accumulates in the atmosphere each year and drives climate change (Lal, 2008). However, in comparison to the massive amounts of carbon in the soil and the vast natural flows, the human contribution appears minuscule. Could the natural cycle be tweaked to squeeze some of this excess carbon into the soil? With proper management, says Smith, soil could hold an extra 1–1.5 Gt of carbon annually for 20–50 years. ''Obviously, a very small change in the soil carbon can have a very big influence on the atmospheric carbon dioxide concentrations,'' says Smith (Smith et al., 2008).

Realizing this potential requires understanding and perhaps manipulating the complex ''below ground'' ecosystem of roots, microbes, and organic matter. Bacteria, fungi, and other soil organisms help turn plant debris such as dead leaves and root secretions into humus, a carbon-rich mixture of stable organic compounds that makes soil rich and fertile; however, in doing so, the organisms also emit carbon dioxide and other greenhouse gases. ''They want to burn up carbon, too, not to store it,'' says Gary King of the Louisiana State University in Baton Rouge, Louisiana. King notes, however, that fungi typically burn up less carbon and store more of it in their cells than other microbes. Certain symbiotic fungi living around plant roots go even further: they secrete proteins that help the soil form granules that protect organic matter inside them from decomposition. ''Our scientific challenge is to move the balance point in a direction that enhances the storage of carbon,'' says King. He points out that this happens naturally in the aftermath of volcanic eruptions, when barren lava-covered landscapes turn into forests in a century timescale. ''The organic carbon in the soil goes from essentially zero to 30% or more,'' he says. ''You have in front of you an example of carbon sequestration taking place in an extraordinary sense.''

Healthy soils typically display a rich, dark color and a moist, granular texture and enjoy a carbon content of 1%–5% or more. ''Carbon is central to soil quality,'' says Chuck Rice of the Kansas State University in Manhattan, Kansas. ''Putting carbon back in the soil will not only make it more productive, but also more resilient to the changing environment.'' Unfortunately, modern agricultural practices such as tilling and removing crop residue have the opposite effect. They dry up the soil and break up its granules; the exposed organic matter quickly oxidizes or decomposes. The soil ends up with a pale color and loose, dry, clumped appearance. It holds less water and fewer nutrients, becomes less fertile, and erodes easily. It loses the flourishing microbial ecosystem needed to maintain a healthy amount of carbon. After decades of such treatment, many agricultural soils, especially in the tropics, have as little as 0.1% of carbon left. Land use changes can also damage soil health. When grassland is tilled and cultivated, it typically loses 1–2 tons of carbon per hectare (about 2.5 acres) each year. ''Tilling and removal of plant residue are the two biggest causes of soil degradation,'' says Jerry Hatfield of the USDA National Laboratory for Agriculture and the Environment in Ames, Iowa. ''The easiest way to reverse this is to go to a very low tillage system.''

What we grow on our croplands may be just as important as *how* we grow it. Most wild plants are perennials with a deep, strong root structure that helps nourish and stabilize the soil they grow on. Most agricultural crops such as wheat, rice, corn, and soybean, however, are shallow-rooted annuals that don't provide the same soil support. As a result, even well-managed cropland soil often suffers from poor quality and low carbon content. Developing food crops with perennial traits could help address this. One approach is to "domesticate" wild perennials by selective breeding until they have high yield, large seed size, and other agronomic virtues. This takes time; a quicker method may be to force a food crop to mate with a perennial relative. In either case, researchers are hoping to create new crop varieties that will not only enhance soil carbon and quality, but also better resist droughts and other adverse conditions thanks to their deep roots. "There isn't anything really not to like about perennial plants with deep roots," says Douglas Kell of the University of Manchester in England, who estimates that such plants could store an extra 100 tons of carbon per hectare in their roots alone compared to annuals.

Biomass such as plant residue or manure when added to soil turns into humic carbon that has a half-life of 25–50 years. To store the carbon much longer, some experts recommend first heating the biomass in low oxygen conditions until it turns into a charcoal-like substance called biochar. Although it can't fully replace humic carbon—it doesn't help soil resist erosion, for instance—biochar, too, can improve soil quality. It tends to work especially well in poor, acidic tropical soils; the fertility of the terra preta soils of the Amazon is attributed to the high amounts of charcoal added to it by natives in pre-Columbian times. Biochar could also help pack more carbon into humus-rich soils. "If you add any more humic carbon to them, it's going to go right back into the atmosphere," says Jim Amonette of the Pacific Northwest National Laboratory in Richland, Washington. "Instead, if you converted it to biochar first, you might get 50% additional sequestration."

Biochar addition, no-till agriculture, and similar soil-improvement methods, however, will not come cost free. In many parts of Asia and Africa, farmers can survive only by extracting as much biomass as they can from the soil, a practice sometimes referred to as "carbon mining." Plant residue serves as fodder, and animal waste as fuel. With no organic residue left behind, soil becomes dry, infertile, and carbon deficient. Instead of blaming subsistence farmers for this, however, we should offer them suitable incentives for adopting soil-enhancing practices, says Rattan Lal of the Ohio State University in Columbus, Ohio. Unfortunately, attempts to devise such incentives have enjoyed little success. For instance, carbon credits that traded in the now-defunct Chicago Climate Exchange at a few dollars a ton, which is perhaps twice as much carbon as a farmer can hope to sequester per hectare each year by proper soil management, are now worth about ten cents. Lal notes that many widely touted sequestration methods—such as storing carbon dioxide in abandoned oil wells, aquifers, or other geological formations—could cost up to $800 per ton. "Ten cents for soil carbon versus $800 for geologic sequestration—that's what I call bad economics."

Getting more carbon into soils that lack it is a big challenge; keeping the carbon in soils that have it may be a much bigger one. Peat bogs, marshes, and other carbon-rich wetlands are vulnerable to drying from human or climate influences. Once drying starts, deep cracks often form, and the ground dries out even faster; soon, nothing can prevent the stored carbon from decomposing or burning. The world got a taste of this in 1997, when fires in Indonesian peat bogs drained for agriculture accounted for 10% of all human-related greenhouse gas emissions. "Sequestering carbon in agricultural soils is worthwhile, but it's not a panacea for climate change," warns Eric Davidson of the Woods Hole Research Center in Falmouth, Massachusetts. "It could easily be overwhelmed by release of carbon from other soils."

Up north in the Arctic permafrost, the situation could be worse: a huge amount of organic carbon trapped in the frozen ground could escape due to—and then intensify—global warming. Like the drying of wetlands, the thawing of permafrost is often sudden and unpredictable. As large chunks of ice melt, the ground collapses, cracks form, and the exposed surfaces thaw out faster. "When the ground warms, its whole three-dimensional structure changes," says Ted Schuur of the University of Florida in Gainesville, Florida. Unlike dried-up wetlands that could potentially be restored, thawed permafrost cannot be refrozen. Exposed to air, thawed soil carbon could oxidize into carbon dioxide; under water, it could form methane, a 25× more potent greenhouse gas. "We could be looking at hundreds of billions of tons of carbon in the form of CO_2 and methane entering the atmosphere by 2100," says Schuur (Schuur, 2008).

These emissions could cause further warming, greatly amplifying the climate change that triggered them—one of the dreaded "positive feedback" effects on climate. Preventing this from happening should be a major priority, all experts agree. Since we have no direct control over the Arctic environments, soil carbon sequestration and other climate mitigation efforts elsewhere assume an even greater urgency, says Schuur. "We shouldn't throw up our hands but realize that it's twice as important now."

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