Turning air into dirt:
Using atmospheric carbon and solar energy to build the water-holding soils that can feed the world

Our best opportunity for an effective, near-term, and broadly inclusive strategy to address climate change lies beneath our feet. The soil contains more carbon than the atmosphere and forests combined. Though human actions and decisions control them, these enormous flows of carbon in and out of the soil are invisible, and largely outside our awareness and intention.

We can take advantage of this opportunity if we can see it. What follows is not a pet theory or idle speculation. It is based on years of on-site reporting on farms and ranches on several continents.

Technology alone, or guilt over technology, won't fix climate change. Fossil-fuel burning contributes only about 3.4% of the annual global flow of carbon dioxide into the atmosphere. Deforestation or land use change, about 0.75%.[1]

Though just a sliver relative to the big picture, these emissions contribute to the likelihood of dangerous climate change. They're bad. But what might happen if we reduce them, or stop them?

In 2007 the Intergovernmental Panel on Climate Change noted that "both past and future anthropogenic carbon dioxide emissions will continue to contribute to warming and sea level rise for more than a millennium, due to the time scales required for removal of this gas from the atmosphere."[2] Furthermore, "complete elimination of CO2 emissions is estimated to lead to a slow decrease in atmospheric CO2 of about 40 ppm over the 21st century."[3] In other words, with the stiffest reductions imaginable, it may take generations to get atmospheric concentrations down to what climate scientist James Hansen calls safe levels—350 parts per million.

Burning fossil fuels and forests also generates aerosols or fine particles that reflect solar radiation back into space, with significant cooling effects.[4] Loss of these short-lived aerosols would likely result in immediate warming.

Stopping the bad things won't fix it. Interconnected processes are moving at different tempos, with turbulence and multiple feedback loops, making accurate predictions difficult. But it appears that the emissions reductions many people are pushing hard for—claiming extreme urgency and overriding importance—will not give us climate security anytime soon. Reducing fossil-fuel emissions is a necessary part of **long-term** climate stability. But in the near term, emissions reductions would have little leverage on the factors of concern: positive radiative forcing caused principally by atmospheric carbon dioxide.

When we identify climate change as an environmental problem, where human technology and greed do bad things to the environment, our process of devising a solution is reflexive and instantaneous: stop or reduce the bad things. We call it pollution, a moral issue. Problem and solution are joined at the hip. We might debate the merits of regulation, taxes and cap and trade, or research and investment in alternative energy, but these are minor schisms within a larger creed.

It is difficult to point out the shortcomings of an emissions reduction focus without appearing to deny that humans cause climate change, and being labeled a climate crank or worse. When problem and solution are joined in a moral equation, policy debates drift away from pragmatic solutions. Opportunities that might not fit with this moral framework go unrecognized. Activists and skeptics remain locked in positional struggles, which may appear to be over science and policy, emissions reduction targets, timetables, and methods—but they are persistent conflicts over moral perceptions and values.

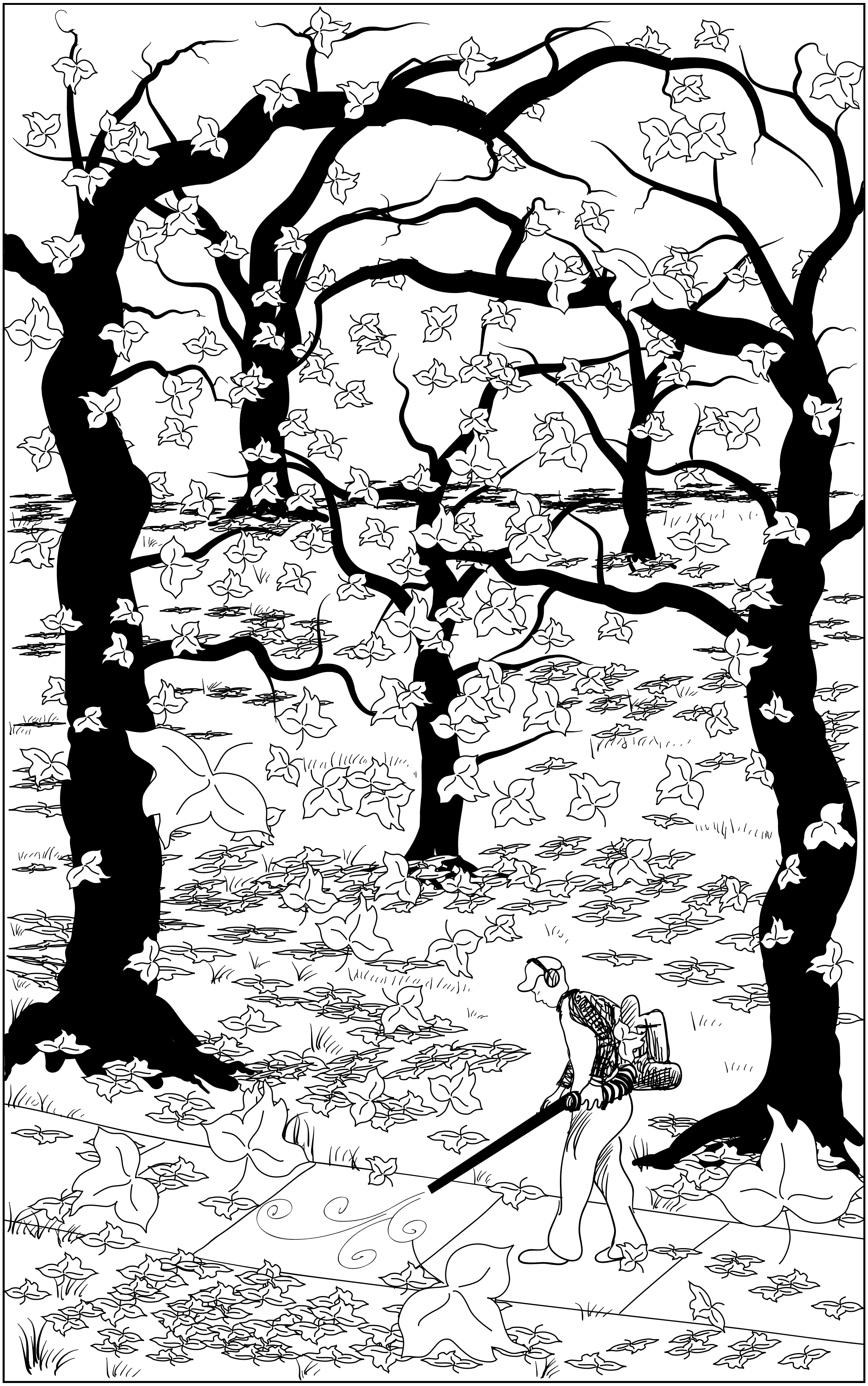
Taking responsibility means seeing the problem differently. The problem with carbon is that it's **not** a problem. It's a biologically driven cycle. It's a network of self-motivated creatures, most of them microscopic, powered by sunlight transformed into chemical bonds, who grow, eat, multiply, respire, and die.

Our institutions, programs, policies—even the way we think—are hardly suited to recognize or imagine, let alone manage, such complexity. We're better at simplifying things, at reducing diversity. We're better suited to tackling technical problems and short-term logistical challenges: putting men on the moon, shrinking the ozone hole, reducing acid rain, zapping the Y2K bug.

Carbon looks like this kind of problem to us because we're looking at it through a keyhole. We're focused on the sliver of the carbon cycle that we recognize, through a familiar moral framework, as our fault: fossil-fuel burning and deforestation.

If we stop this bad stuff, we're still in deep trouble from climate change. Refusing new "bad stuff"—ocean iron fertilization, space reflectors, sulfate particles into the stratosphere, or nuclear power to replace coal—won't protect us either. All we can do is wreck the world slower. Indecision and procrastination may appear strategic, even urgent.

The secret to eternal life on earth is the carbon cycle. The U.S. Supreme Court's recent decision notwithstanding, carbon dioxide is not a pollutant. It is the atmospheric supply from which photosynthesis makes the chemical skeleton of all life, and the carbon compounds that power every action, feeling, and thought. Our human participation in—and responsibility for—the carbon



cycle is not just one-way “emissions,” smokestacks and exhaust pipes, our so-called footprint. It includes every bite we eat, every breath we exhale, and our participation with the whole of life.

Green plants take carbon from the atmosphere. They turn solar energy into chemical energy, building the carbon-chain sugars and carbohydrates that fuel life and growth. These compounds move through complex foodwebs, releasing their chemical energy through oxidation reactions such as respiration, decay, or fire. The carbon returns to the atmosphere, mostly as heat-trapping carbon dioxide.

There is also a slow geological carbon cycle, between the atmosphere and rocks via volcanoes and rock weathering, sedimentation, subduction, and uplift. But this is tiny compared to the big fast biological cycle.

The ocean, which contains vast amounts of carbon, buffers the atmosphere through an exchange based on the solubility of carbon dioxide rather than directly on life’s capture and release of solar energy.

As carbon flows around the biosphere, some of it lingers in eddies or pools, where oxidation (death, dissolution, and decay) lags behind photosynthesis (life, growth). The average level of carbon dioxide in the atmosphere is the running total of oxidation minus photosynthesis, buffered by the ocean (the Keeling curve).

1. The biomass pool. Starting from the atmosphere, the first pool is the stuff of living organisms. Half the dry weight of biomass is carbon, captured from the atmosphere by solar-powered photosynthesis. Three-quarters of this biomass is wood. A coarse global average is that about 10 percent of biomass dies each year, and 10 percent is new growth.

We have some influence over these rates, and the biomass carbon pool could be expanded. However, the easy oxidation of biomass through fire and decay is a constant and increasing threat. Forests don’t produce much food, and competition for land on the part of farmers and graziers will continue.

Though biomass is the smallest of the pools, with the most rapid turnover, it is the source for the others, which are progressively larger, older, and more stable.

2. Soil pool. The second pool is on and in the soil. As plants and other organisms die, their residue becomes organic litter on the soil surface, and dead roots below the soil surface. If oxidation can be postponed, soil microbiology will transmute some of this residue into an enormous complexity of carbon compounds. This is soil organic matter—the detritus of past life, the present habitat for enormous underground biodiversity, and the substrate for future life, including the crops that feed us. Like the life it came from, it is half carbon if you remove the water—and soil organic matter can hold many times its weight in water.

Soil organic matter gives topsoil its life, quality, and much of its capacity to accept and retain water. It is the difference between the dirt under a porch or an old building, and the living topsoil from a lawn or garden that has fragrance, crumb structure, holds water, and contains millions of organisms per teaspoon.

While litter oxidizes readily, most soil organic matter is more resistant—unless the soil containing it is tilled or exposed to the air, where abundant microbes oxidize it rapidly. Because of the way perennial grasses slough roots and carbon-rich substances to the soil, the world's grasslands can pump tremendous amounts of carbon underground. Over the last 150 years, around the world, much of these underground reserves have been plowed, oxidizing immense amounts of soil organic matter into atmospheric carbon dioxide. Yet this little-understood soil pool still contains more carbon than the atmosphere and biomass combined. On average, a little over 3% of the soil carbon pool turns over every year.

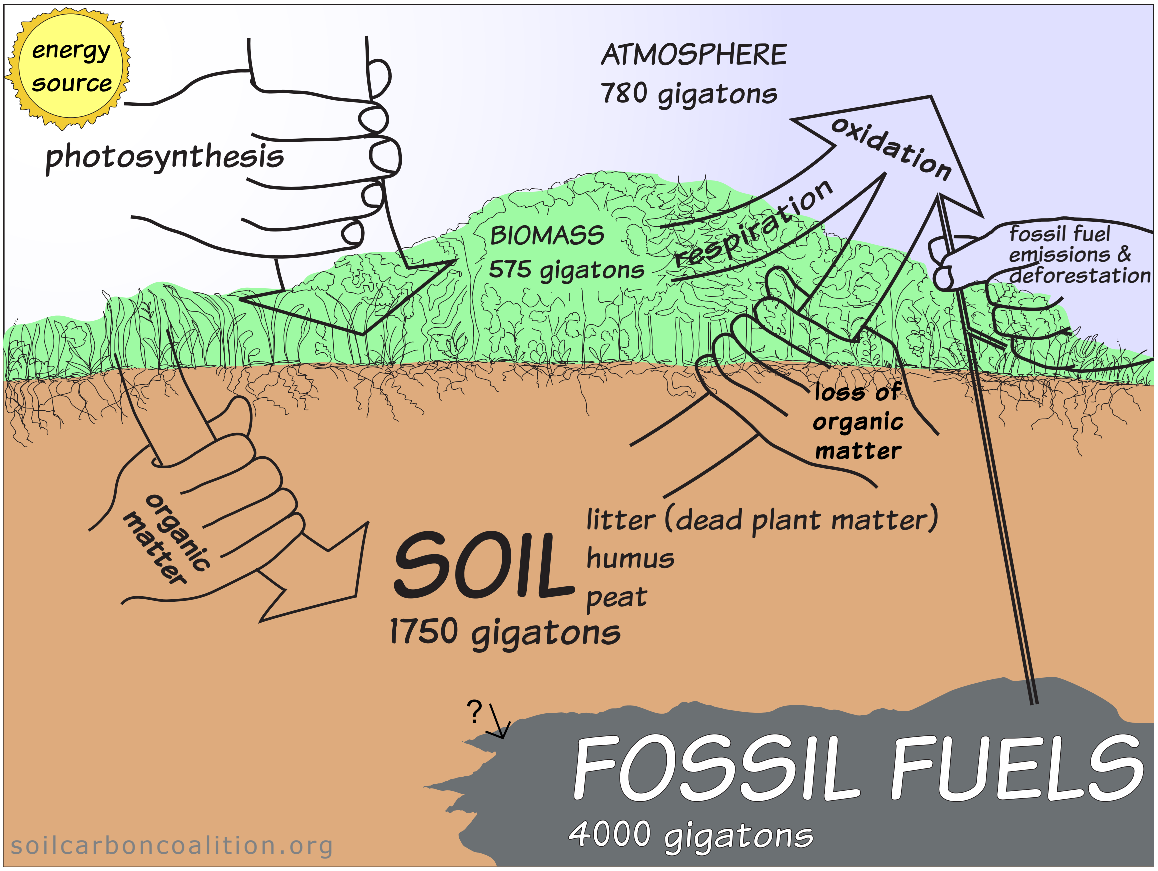
3. Fossil fuels. The largest and oldest carbon pool in significant interaction with the atmosphere is coal, oil, and natural gas. These come from the richest forms of soil organic matter, such as peat, protected from oxidation and transformed through pressure and geologic spans of time. Though we are unlikely to be able to assist the formation of fossil fuels, we could slow the rate at which we oxidize them.

Oxidation has been exceeding photosynthesis, so we have too much carbon in the air, and not enough in these pools. Carbon sequestration is about increasing the pools, using atmospheric carbon as the source. But there are two directions to choose from.

One, commonly called carbon capture and sequestration (CCS), involves a sort of oxidation reversal, capturing carbon dioxide from flue gases or from the atmosphere and pumping it underground. The stability of such reversals, and the enormous materials-handling challenges, have been rightly questioned. But the formidable energy costs of such reversals are often ignored or forgotten.

The other is with photosynthesis, using solar energy. This biological energy dwarfs the industrial kind. In harnessing it to sequester carbon, everything else looks ineffective or roundabout by comparison.[5] But doing so will require change.

For tens of thousands of years, since we became the biosphere's principal arsonists, humans have made a specialty of oxidation. And it's not just fossil fuels or tropical forests that we're oxidizing. With the plow, and with our neglect of the complementarity between grasslands and grazing animals, we

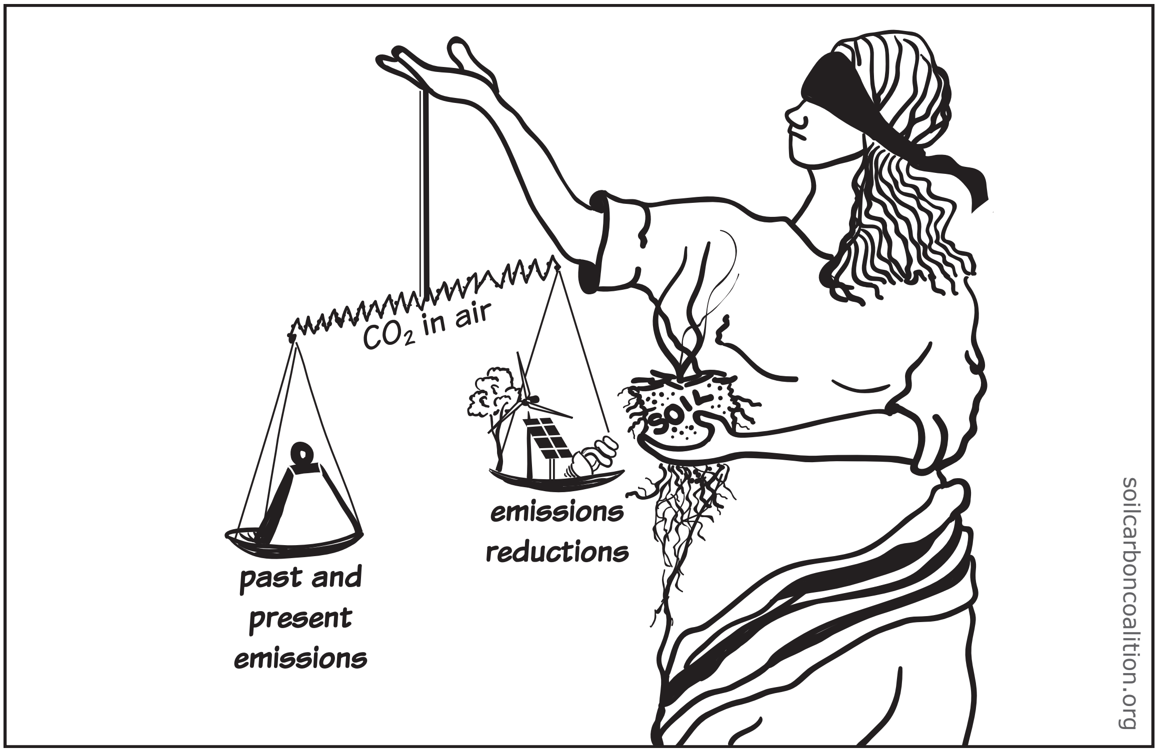


The main flows of the terrestrial carbon cycle, showing human influence. A gigaton is a billion metric tons. Solar energy drives the cycle, moving in counterclockwise direction. Reversing portions of the cycle (e.g. using technology to capture carbon dioxide from the air and pumping it underground) will require energy.

have suppressed vast amounts of photosynthesis while speeding the exposure, erosion, and oxidation of organic matter, both on the soil and in the soil. With herbicides and an increasing appetite for fossil energy, industrial agriculture has taken oxidation to a new pinnacle of efficiency.

But humans didn't do these things with the intention of unbalancing the carbon cycle. And now there is a countertrend. Several varieties of alternative agriculture have discovered how to lower costs and increase food production. A corollary is increased photosynthesis and reduced oxidation, and a potentially large impact on carbon cycling. It is not necessary to oxidize much of the soil organic matter in our soils to produce food. It is a matter of method.

Complexity and self-reinforcing feedback. These methods vary by location and practitioner, because the carbon cycle functions differently according to location, and the rapidity or slowness of the decay of plant material. But



We can balance the carbon cycle with soil carbon. It's only fair, and offers needed near-term leverage.

there are some common principles. Instead of regarding biological diversity as competition, and declaring war with increasing inputs of technology and chemicals, these methods practice complexity. They maintain and enhance biological diversity both above and below ground. Synergy—between animals and plants, between one crop and another, between microbes and plants, between soil organic matter and water retention—drives a self-reinforcing feedback, or virtuous cycle, that can outproduce at lower cost the simplified input-dependent monocultures that have been the industrial ideal.

Management of the soil surface is the key. Soil cover—whether plant litter, crop residue, mulch, or living plants—is essential to feeding the microbial life of the soil and building soil carbon. With increasing photosynthesis from complex polycultures of grasses and forbs for example, there can be large increases in the production of organic matter. Well-timed and managed grazing, combined with insects, earthworms, and a vast array of microbial life, can turn much of this into stable soil organic matter, highly beneficial to the resiliency and productivity of landscapes.

Even poor people can do this, because the input need not be machinery, fuel, or fertilizer, but management that understands how to enhance complexity in carbon cycling, water cycling, and the flow of solar energy. This amounts to working with rather than against nature, or the metabolisms of the biosphere. Farmers, ranchers, and land managers can now choose to build soil instead of degrading it, using photosynthetic solar energy.

The potential. Estimates vary of the potential tonnage of soil carbon sequestration, and its effect on atmospheric concentrations. All estimates or projections involve chains of assumptions, usually undeclared. For example, the more conservative assumptions of soil potentials may assume that agricultural practices won't change much, that soils cannot hold more carbon than they did in the past, that soil building is a slow geological process, that many soils have low potential, and that negative feedbacks such as the costs of change will further limit the potential. Research projects involving typical practices, on soils that have been degraded by years of industrial monocultures, tend to bear out these low estimates.

Others point out the best examples, where innovative managers have doubled or tripled their soil carbon in pursuit of sustainability. The assumptions are that significant change is possible, in part because of synergy between microbes, plants, and livestock for example, and that managing for such synergy is something anyone can do if they so choose.

Given that soils contain more than twice as much carbon as does the air, slight changes in soil can have major impacts. For example, reducing atmospheric concentrations from the current 387 to 350 parts per million would only require a 4.2% increase in the size of the organic carbon pool in the soil, if we ignore the delays of ocean buffering. To offset or equalize the current rate of growth of the atmospheric pool, again ignoring ocean buffering, would require the soil organic pool to increase by less than a quarter of a percent per year.[6] The carbon pool represented by soil organic matter, by virtue of its size, stability, and the volume of yearly flows in and out, can provide needed leverage on the global carbon cycle.

And we humans manage the soil pool. Farmers and graziers worldwide control the formation and release of the majority of soil carbon through their management of the soil surface. In the past and present, much of this management has led to huge but unintentional losses of soil carbon to the atmosphere. But carbon farming—turning air into soil—demonstrates that these losses can be reversed, using solar energy and microbiology to build the water-holding soils that will feed the world.

In many parts of the world, methane-emitting ruminant animals can be an effective low-cost tool to maintain the health of perennial grasses, and rebuild carbon-rich grassland soils. The rich grasslands of North America, under which were tremendous reserves of carbon-rich soil organic matter, were maintained and enhanced by vast herds of migrating bison. Modern grainfields and feedlots take a coevolved ecological whole—grasses, grazers, pack-hunting predators that kept the grazers bunched and moving, microbes and various other soil creatures—and break it apart into numerous problems that cannot be solved in isolation from one another. Methane from livestock is just one.[7]

We take soil for granted. The discovery of soil building, which has perhaps been made and forgotten in various forms over the millennia, doesn't make headlines. A soil-regenerative agriculture doesn't match our mental models of environmental solutions (stopping the bad stuff) or technological innovations.

The exception might be biochar or terra preta, the ancient Amazonian practice of amending soils with charcoal. Partial combustion of biomass stabilizes subsequent decay and oxidation, thus sequestering carbon, and enhances beneficial microbial activity in many soils. Results can be similar to biological soil sequestration, but the use of technology and fire (in high-tech pyrolysis) to create a soil amendment is easier to recognize.

If turning air into dirt with living organisms remains difficult for us to understand, to recognize, or even to imagine, how will we realize the opportunity?

The system cannot change itself. The thinking or decision making that created the climate problem is not the kind that can solve it. Transformation of agriculture will not occur from the top down, from international agreements, or through research seeking best management practices. These agricultural innovations for soil organic matter have not come from the centers of institutional and economic power, or from the flagship issues of the environmental movement. They have come from the edges.

There is too much carbon in the atmosphere, and not enough in the soil. Various forms of alternative agriculture have figured out how to move carbon from one to the other, to turn air into soil. Soils are the largest expandable carbon pool that we control, that has the needed leverage over atmospheric concentrations.

There are plenty of institutions and organizations devoted to protecting species, forests, and landscapes, advocating reduced fossil fuel emissions, and locally grown food. But there is no major government or academic department or major environmental organization for carbon cycling, photosynthesis, or organic matter. For the most part, our government departments of agriculture remain aligned with industrial practices on degrading soils, and our environmental organizations with regulations, stopping the bad stuff.

Soil policy has remained isolated from major issues such as the economy or climate change. That soil is mainly a geological formation, that it takes a thousand years to create an inch of topsoil, is still the basis for much policy. The separation of physical and biological science continues to impede our understanding of soils, of climate change, and the carbon cycle.[8]

With the fragmentation of both science and advocacy, we tend not to be aware of what we don't know. Research and prediction help us focus on what we know. But for wicked problems such as climate change, water scarcity, and food security, this should not be our only strategy. The major risks, as well as the major opportunities—the so-called tipping points—will come from unexpected quarters.

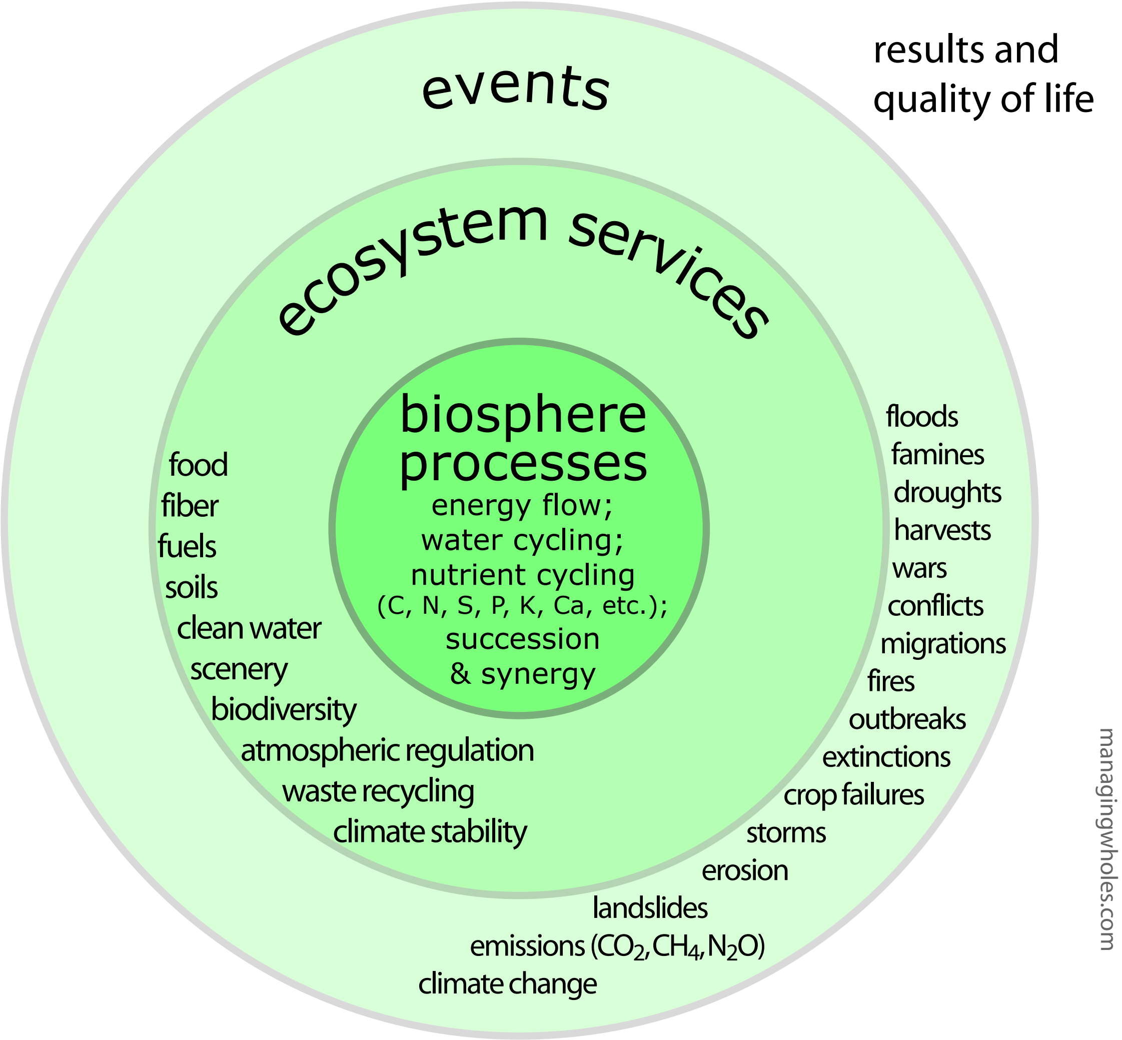
The lack of vested or institutional interests in soil organic matter means that we will have to take responsibility as a people. Taking responsibility means deferring the question, "What should we do?" because this question tends to privilege established ways of thinking, knowing, and doing. We need to ask first:

1. How does the carbon cycle work, locally and globally?
2. How have we affected the carbon cycle, and what are we currently doing?
3. What's possible, and who is showing the way forward? (For example, looking at those who have rapidly increased soil organic matter.)

Monitoring and navigation. All three questions require monitoring or navigation—understanding where we are, where we want and need to be, and the direction of the difference. Navigation is goal-directed, whereas much scientific research is aimed at documenting what happened, and knowledge that leads to prediction rather than effective action.

When dealing with complexity such as the carbon cycle, navigation beats prediction. The best way to predict the future is to create it. Navigation or monitoring is creative because it privileges what works, instead of what ought to work. It frequently challenges our beliefs. Because it is goal-directed, it allows us to encounter the boundaries of our knowledge. In situations of complexity and uncertainty, monitoring can be a powerful selective force for locally adapted strategies and pragmatic solutions.

Stopping the bad things isn't enough. We can take responsibility for carbon cycling in broader, more effective ways. Though there aren't vested interests or established policies to do this for us, we have tremendous opportunities to enhance the formation of soil organic carbon through policy changes at all levels as well as through individual decisions.



On what level are we focusing our efforts? If we want to transform the situation, where is the center of gravity? Where can self-reinforcing (positive) feedback create fundamental shifts? For millennia, we've focused on the outer layers. We judge events, outcomes, and species as good or bad, and we are in conflict over which ones are good or bad, natural or unnatural, native or nonnative. We cannot seem to find a balance of nature while our focus remains on the periphery.

Taking responsibility must include monitoring. If monitoring were widely practiced, we might see the following:

"Climate friendliness" would be assessed according to soil carbon as well as fossil fuel emissions. Food raised on perennial grass pastures, as described by Michael Pollan in *The Omnivore's Dilemma*, may turn out to be far more climate friendly than tofu from a soybean monoculture with regular tillage. Consumers could exert a powerful selective force for a climate-friendly agriculture.

By including land managers in the solutions, the politics of climate change would undergo a sea change. Markets for ecosystem services such as water would improve urban-rural relations and strengthen communities.

Soil organic matter, and the enhancement of basic biosphere processes, would become the center of gravity of the U.S. Farm Bill as well as of U.S. public land policy. Results would include drastically reduced flooding, better human nutrition, stronger rural communities, increased biodiversity, reduced wildfires and landslides, and cities with more secure water supplies, as well as decreased atmospheric carbon dioxide and reduced threat of climate change.

Internationally, results may be similar. With increased soil fertility and food production, forests and biodiversity are less threatened, and farmers and graziers everywhere are able to contribute to solving climate issues, rather than just hoping that the industrialized world will do something about fossil fuel emissions. In building soil organic matter, farmers are less dependent on the farm input sectors that become such large and powerful vested interests. Building water-holding soil with solar energy that feeds people provides hope to millions.

How can people (many of whom are not land managers) take broader responsibility for the carbon cycle, this complex biological network of self-motivated organisms? And how do we engage in, support, or encourage the monitoring of soil carbon? Please enter your suggestions as comments, and if they are based on personal experience, so much the better.

You can also contribute to the Soil Carbon Coalition's World Carbon Cup (soilcarboncoalition.org/contest), a prize competition that will highlight the possibilities of using atmospheric carbon to build water-holding soils that can feed the world.

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Notes

[1] These and other estimates of carbon fluxes and pools are from Rattan Lal, Sequestration of atmospheric CO2 in global carbon pools, *Energy and Environmental Science* 1, 86–100 (2008). The percentages can be calculated from Lal's Figure 1. A similar, more accessible but somewhat dated numerical description of the carbon flows and pools is on the NASA website at www.earthobservatory.nasa.gov/Features/CarbonCycle/carbon_cycle4.php (diagram near bottom).

[2] From IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

[3] From the IPCC FAQ on the Physical Science Basis of Climate Change, section 10.3 (2007), ipcc-wg1.ucar.edu/wg1/FAQ/wg1_faq-10.3.html

[4] From the IPCC FAQ on the Physical Science Basis of Climate Change, section 2.1 (2007), ipcc-wg1.ucar.edu/wg1/FAQ/wg1_faq-2.1.html. There is large uncertainty about the cloud albedo effect, which would decline if particle pollution were to lessen substantially.

[5] Thanks to Christine Jones for the phrase. Because the carbon cycle is inextricably tied to energy, it is worth noting that photosynthesis annually embodies, in chemical bonds, 8 or 9 times the industrial and fossil energy that the world uses, despite the fact that photosynthesis routinely captures only about 1 percent of the available solar energy that strikes a green leaf. This energy is released, often in partial stages, by oxidation.

[6] These simple calculations are based on Rattan Lal's numbers on the global carbon cycle referenced in note 1.

[7] For some more detail on the livestock methane issue, see www.eatwild.com/environment.html and www.soilcarboncoalition.org/methane.

[8] In the 1920s Russian geochemist Vladimir Vernadsky, far in advance of conventional scientific understanding, noted that "life is the most powerful geological force." James Lovelock also noted that the disconnect between physical and biological sciences has impeded our understanding of climate change: "If you look back at the writings of Earth scientists forty years ago you will find them confident that the composition and climate of our planet were completely explicable from chemistry and physics and that life was just a passenger. Life scientists of the same time were equally confident that organisms evolved according to Darwin's great vision and adapted to the Earth described by their Earth science colleagues in the building across the campus. This harmful and irrational division of science is slowly fading but it still persists and has led to the deplorable separation of the assessment of global change between two different international bodies: one based on physical science, the IPCC, and the other on biology, the Millennium Ecosystem Assessment. The Earth is not so divided and so long as we treat it as two separate entities, the geosphere for the material Earth and the biosphere for life, we will fail to understand our planet." From 'Climate change on a living earth', Lecture to the Royal Society 10/29/07. www.royalsociety.org/page.asp?id=7250