Chapter Five
The Biology of Soil Carbon

The Fundamental Importance of Soil Carbon

The Carbon Cycle

The carbon atom, often referred to simply as C, is fundamental to life. It is the basis for all organic chemistry, which is the chemistry of all living creatures, from microbes to elephants and whales. The incredible all-important process we know as photosynthesis, whereby plants convert energy from the sun into the biochemical energy that supports life, revolves around C. Plants take in carbon dioxide (CO_2) from the atmosphere, split that molecule into its oxygen (O_2) and C constituents, release the O_2 back into the atmosphere, and then build sugar molecules using the C as a base (the other major input, hydrogen, comes from water, or H_2O).

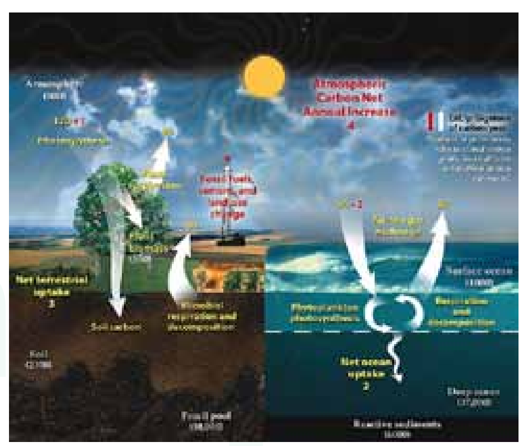
Although the full story of how energy is transferred, used, and dissipated by life forms is long and complicated, all we need to say here is that carbon is the energy currency of life. In the human world, our various currencies (the units we call "money") are simply representations of more basic forms of energy, such as human labour. Carbon, however, is the most fundamental currency of them all, for it is needed in all forms of biochemical energy, from basic respiration to the most complicated of our human endeavors.

Value of Carbon in Soil

Soil organic matter, or SOM, is usually about 58 per cent carbon. It is the C in organic matter that provides the creatures of the soil food web with their energy, so it makes sense that higher SOM levels means more energy for soil microbes. More energy for soil microbes in turn should translate into stronger soil functions, that is, better soil structure (Chapter Two), better natural fertility (Chapter Three), and greater disease and pest suppression (Chapter Four). As discussed in these previous Chapters, better soil functions represent a large number of "free" benefits to farmers. In other words, the more soil carbon, the better.

In fact, many people think of soil carbon levels as being a good measurement of soil health. That is not completely true, however, as factors such as diversity (and even productivity) are not always directly related to soil carbon levels (more on this in Chapter Six). Nevertheless, SOM levels are probably as good a measure of the potential for healthy soil as we currently possess.

Figure 37 shows the basics of the Carbon Cycle – the system by which carbon moves between its various pools on the planet, including soils. Worldwide, our agricultural soils have been losing C for a long time. Some feel that the beginning of the loss of soil C goes back to the beginnings of agriculture, about 10-12,000 years ago, when the concept of stirring up or tilling the soil first developed. This may or may not be true, but it certainly does seem to be the case that agriculture has had a very big negative impact on the amount of carbon stored in the planet's soils. Recently, researchers have estimated that about 8 per cent of total global soil carbon stocks may have been lost from the top two metres of the world's soil since agriculture was introduced – a total of 133 billion tonnes. This figure represents all soils (forests, prairies, farmland, etc.) -- the amount lost from agricultural soils worldwide is estimated to be much higher -- between 30 and 60 per cent. Moreover, the rate of loss has been increasing since the industrial revolution.



Carbon Cycle *(Figure 37)*
Source: Diagram adapted from U.S. DOE, Biological and Environmental Research Information System

The Climate-Change Connection

The planet's climate is changing. This is no longer just a theory; we see it around us every day, in terms of things like the frequency of weather extremes, or the slow march northward of what we call "plant hardiness zones" (along with the pests, diseases, and invasive plants that come with warmer weather). It is also generally accepted, (by almost all scientists, if not yet all politicians), that the changing climate is a result of more CO_2 (and other greenhouse gases, such as methane) in the atmosphere, and that the increase in these gases is largely due to human activity. Of course, the main culprit is the burning of fossil fuels. However, recent estimates put the contribution of agriculture to this atmospheric CO_2 excess at somewhere between 10 and 20 per cent.

While that may be bad news, it has a flip side that is nothing but good news. This is where soil health can really punch above its weight, as the saying goes. Soils already hold about three times as much C as the biosphere (all living creatures), and that is after losing the 133 billion tonnes of C mentioned above. In fact, the C deficit we have produced in agricultural soils over the past 10,000 years or so offers us a tremendous opportunity to help slow climate change by pulling C back out of the atmosphere and storing it in soils, where it does nothing but good things.

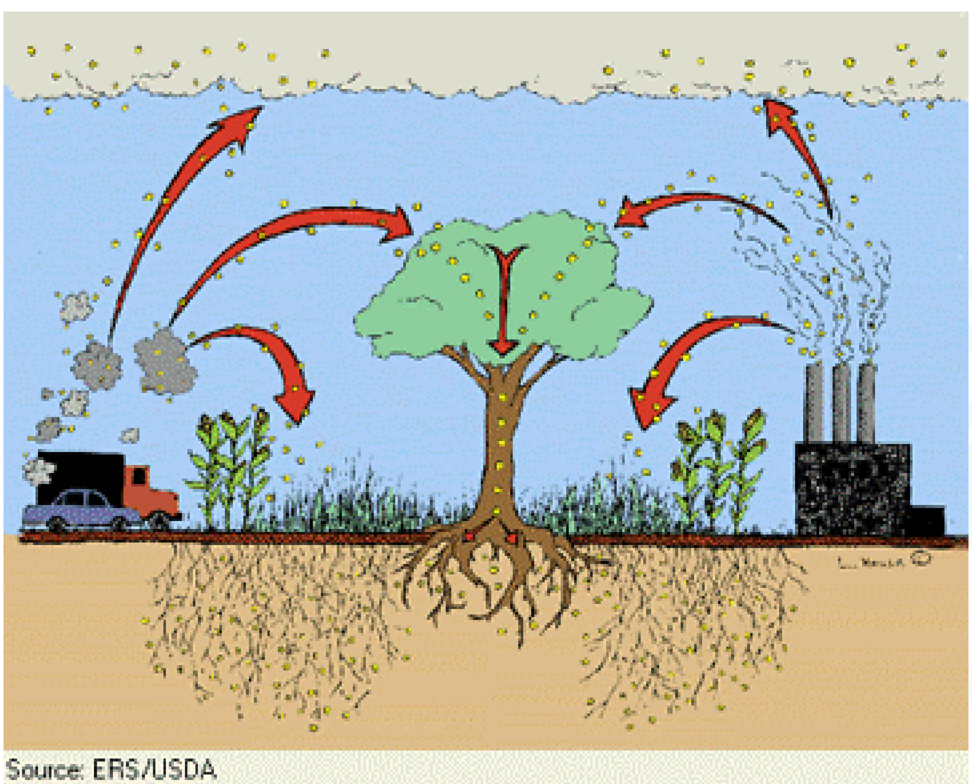
The remaining sections in this chapter are devoted to discussions of how we can put carbon back into our soils – a process known as *soil carbon sequestration* – and how the creatures of the soil food web are vital to this process.

Soil Carbon Sequestration

How Quickly Can Soils Sequester Carbon?

Nobody really questions whether or not soils can sequester carbon (see **Figure 38 – Soil Carbon Sequestration**); it is virtually a given among experts that they can, and that we should try to help them do so. What is being debated, quite vigorously around the world, is "how quickly can we build carbon levels in soils?".

The IPCC (see definition, following page) has estimated that agriculture as a whole could sequester 1.1 to 1.8 tonnes of CO_{2e} per hectare (ha) per year (see Box on "Carbon vs CO_2 equivalents"). This is a fairly significant amount. For instance, the United States Environmental Protection Agency (US EPA) has stated that an automobile, driven by an average driver, generates 4.7 tonnes of CO_{2e} per year. Even if we assume the lowest end of the IPCC estimate (1.1 tonnes/ha/yr), a 500-hectare farm, practicing proven methods for sequestering carbon, would offset the greenhouse gas (GHG) emissions of 117 cars annually. At the high end (1.8 tonnes/ha/yr), that same 500-ha farm would offset the GHGs of 192 cars annually.



Soil Carbon Sequestration *(Figure 38)*

The IPCC estimates are considered by many people to be very conservative. For instance, in a 2016 Report on soil health by the Environmental Commissioner of Ontario, soil-carbon data from an Ontario farm, collected over 20 years, was analyzed. The annual increase in carbon on that farm, where a number of soil-health practices have been employed for several years, and no tillage has occurred since the first soil carbon levels were measured, was calculated to be 4.75 tonnes of CO_{2e} per hectare per year (1.3 tonnes of soil C per ha per yr). This level of sequestration represents the removal of 505 cars from the roads each year. A look into the anecdotal literature on soil carbon sequestration available on the internet will show that similar, and sometimes even higher, figures are common among soil health practitioners.

These higher potential sequestration rates have not been accepted by everyone; in fact, some scientists consider them to be impossible and believe that the higher rates found are a result of incorrect sampling, not sampling deep enough in the soil, or other such technical issues. In 2007, a review of the potential of soil carbon sequestration rates was done for central Canada. The authors of that paper determined that a realistic rate for Ontario soils would be 0.36 to 1.1 tonnes of CO_{2e}/ha/yr.

Why the difference? It may have something to do with the way in which carbon storage is defined, which has to do with how permanent that storage should be considered. It may also be that the science is still evolving. Some of the newest research seems to indicate that the old ways of understanding and predicting carbon storage in soils are incomplete. The following section discusses these issues in more detail.

The IPCC

The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the science related to climate change. The IPCC was set up in 1988 by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation.

Soil Carbon vs Carbon Dioxide Equivalents

When in the soil, carbon is usually in a biochemical form, ranging from fresh plant residues to older, more stable forms of organic matter traditionally known as humus. Accordingly, it is measured as a weight, i.e., *tonnes of soil organic matter (SOM)*, or as a weight of pure carbon, i.e., *tonnes of C* (carbon is, on average, 58 per cent of SOM). However, in the atmosphere, C is in the form of CO_2 – a gas – and it is as a gas that carbon has its impact on climate. Therefore, C in the atmosphere is usually measured as tonnes of CO_2. When converting from soil C to atmospheric CO_2, we need to multiply the weight of C by 3.67 to get the equivalent weight of CO_2 (this is because the weight of two oxygen atoms has to be included with the weight of the C atom). When we do this, we call it the CO_2 equivalent, usually written as CO_{2e} – the amount of atmospheric CO_2 represented by the C measured in the soil.

How Does the Process Work?

So how do soils capture and hold carbon? As with the story of natural soil fertility (Chapter Three), there is an older version and a newer version. Let's start with the older version. Until fairly recently, it used to be thought that soil carbon came mainly from organic residues, e.g., crop residues, animal manures, and dead insects, animals, etc. Therefore, by this logic, if you want to increase the level of carbon in your soil, leave as much of your residues on the soil as possible (or till them in), and add as much manure and/or compost as you can. Also, since carbon levels are a result of the balance of carbon coming in vs carbon going out, you would want to try to limit the latter if possible.

The C going out is largely a result of microbe metabolism -- they breathe oxygen and respire CO_2, as we do, so they use up the C in the soil as they go about their own activities. This is why no-till has come to be encouraged by soil conservationists -- as a way to keep carbon in the soil. Tillage introduces more oxygen in to the system, allowing decomposer microbes to increase their populations. As they do so, they use up the available C and send CO_2 back into the atmosphere. Limiting tillage reduces the C going out and helps tilt the carbon in vs out equation back towards sequestration (provided you keep good amounts of C coming in).

In addition, soil organic matter goes through a series of stages over time. As it is consumed by microbes, most C is gradually released as CO_2 but some smaller fraction is slowly converted to the more stable forms we call humus. These stable forms are more resistant to microbial degradation and thus stay longer in soils (years or even decades). Eventually, a very small fraction of the original SOM will become what is called *recalcitrant*, or extremely resistant to any kind of microbial degradation. Recalcitrant C can stay in soil for centuries.

When we measure carbon in soils, we are measuring a mixture of fresh C (relatively new residues), labile C (organic matter in the process of being degraded by microbes), and stable C (carbon in various degrees of recalcitrance). The models used to predict soil carbon sequestration are generally based on the degradation rates of the types of residue involved (e.g., lignin is slow to degrade, sugars are quick), soil type, presumed moisture and temperature regimes, and so on. The resulting sequestration rate will depend on how much carbon is added each year compared to how much is lost each year, and the loss rate will depend on how long it takes to turn the carbon into more stable forms, given the environmental conditions.

The older version is completely true, and based on good science. However, as with the fertility issue, recent evidence is indicating that it may be incomplete. Here is why.

It is now understood that much of the C that ends up sequestered in soils comes through plant roots, and not from residues or amendments. Remember those carbon trading systems discussed in Chapter Three? And the soil aggregation processes discussed in Chapter Two? Both play a part here.

Root exudates are, almost by definition, rich in carbon. They are, after all, the direct products of photosynthesis, which converts the C in CO_2 into sugars. As mentioned in the earlier chapters, plants donate a lot of their photosynthate (more than 40 per cent in some cases) to the soil via exudates. They also trade a lot of their photosynthesized C to mycorrhiza, in return for water and nutrients. So, what happens to all that carbon?

Well, a lot of it does get burned up by the microbial community, as part of their metabolic processes (living, eating, reproducing, etc.). But a lot of it also gets transformed into microbial biomass (the structural components of their bodies) and into the microbial glues (Chapter Two) that they use to hold on to soil particles. In the case of mycorrhizal fungi, the glue has a specific name – glomalin – and it appears that this substance, along with the bacterial glues, are not only very important to soil aggregation, but also to carbon sequestration. As the soil aggregates are formed, a lot of the glues, as well as other organic materials, get trapped inside the aggregates. Inside these structures, the carbon is *protected* from attack by decomposing bacteria and fungi, because the internal conditions (low oxygen, for one) are not conducive to bacterial activity. (**See Figure 39**).

These aggregates do break down, but in a healthy soil, they are constantly being rebuilt and maintained. Accordingly, soil C loss from these soils is reduced, tilting the balance towards sequestration. When these factors, previously not considered or under-weighted in the models, are taken into account, it may be that the higher sequestration rates being reported by soil health practitioners are not the result of faulty sampling methods, but the result of sequestration processes not previously considered. The next section reports on a study that lends some support to this interpretation.

The Marin Carbon Project

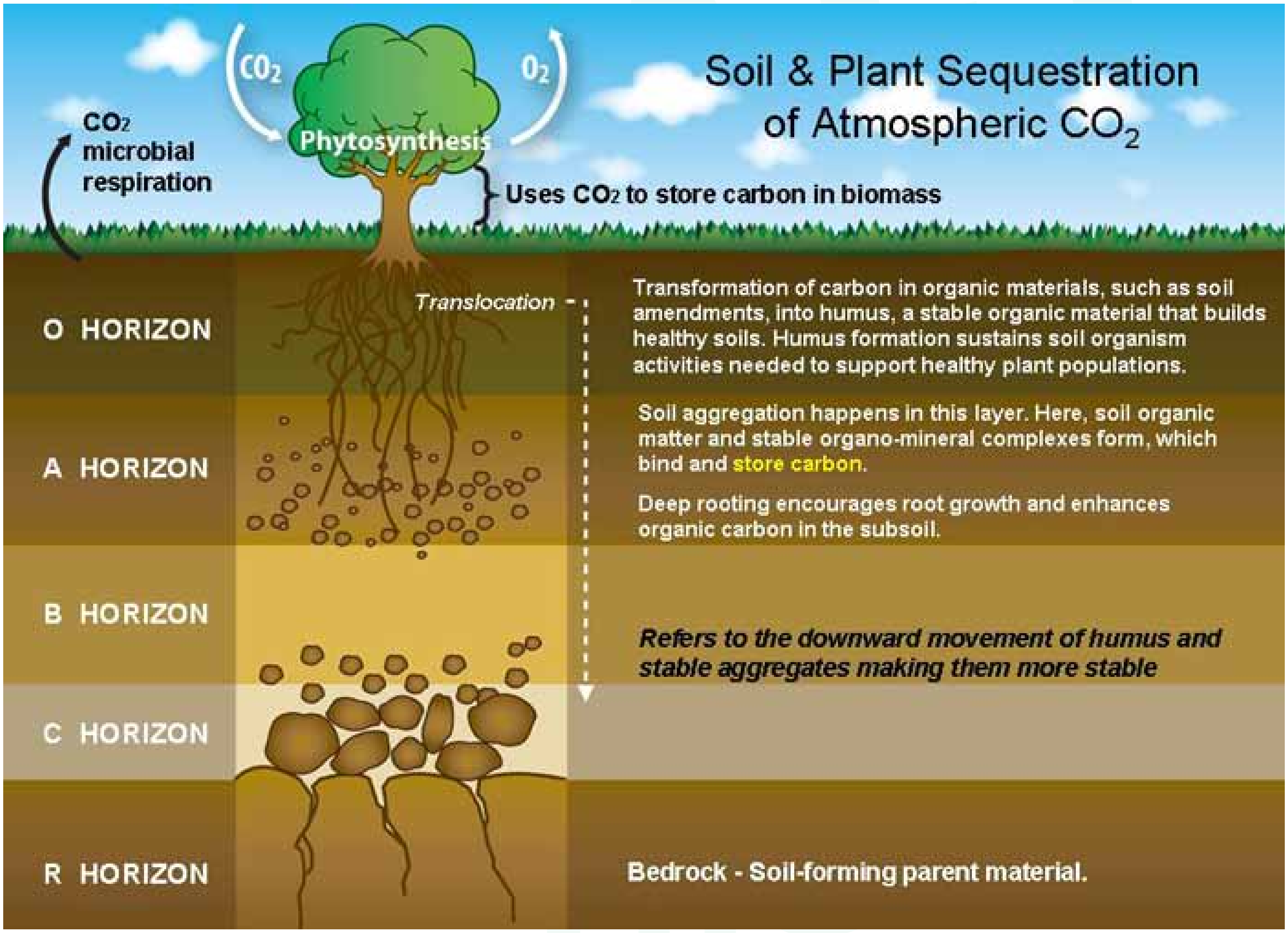
Dr. Whendee Silver, a Professor of Ecosystem Ecology at the University of California, Berkeley, leads a research team that is trying to determine the potential for soil carbon sequestration on range, agricultural, and forest lands in California. They call the it *Marin Carbon Project*. They have plans for the project that go well into the future, but they have just recently completed their first major initiative -- a three-year project on soil-carbon sequestration on rangelands in West Marin County.

After performing "extensive baseline soil sampling and rangeland assessments", they applied 4000 cubic yards of food-waste compost to 100 acres of rangeland test sites situated on three separate farms (see **Figure 40)**. The compost was applied only once, at the beginning of the trials. The team then monitored several factors, including productivity, net carbon sequestration in the soil, and nitrous oxide and methane emissions.

The results of their work support the idea that carbon can be sequestered in soil at higher rates than previously thought. The one-time application of compost had a significant impact over each of the next three years, including:

- A 50 per cent increase in forage production
- An increase of one tonne of C (which translates to 3.7 t CO_{2e}) per hectare per year

Of particular note was the fact that much of the new carbon sequestered in the soil did not originate in the compost – it came via higher residuals resulting from increased growth and from the roots of the plants as exudates and was then incorporated in the aggregates, where it is physically protected from further degradation.



C Sequestration via humus and aggregate formation *(Figure 39)*
Attribution: Environmental Protection Agency (EPA)
https://clu-in.org/products/ecorestoration/seq.cfm#subhead4

Compost Awaiting Application to Rangelands in Marin County *(Figure 40)*

Summary

Carbon, often written simply as C, is the energy currency of life. Plants use photosynthesis to “fix” carbon, transforming it from a component of a gas, CO_2, to the main component of sugar and the other organic molecules that make up the structure of life and provide the energy that drives all living things. A large proportion of this energy ends up in soils via residues (wastes, dead plants and other organisms, etc.) and via plant-root exudates. The creatures of the soil food web use this energy both to live and to create the beneficial soil functions described in earlier chapters. Therefore, the more C we have in our soils, the better.

At the same time, we have too much C in our atmosphere, which is causing our climate to change. This is resulting in more extremes of temperature and moisture and less predictability, which is already impacting agriculture negatively. Most of this excess C is due to the burning of fossil fuels, but some is due to our agricultural practices, particularly the use of the plough. Our agricultural lands have lost between 30 and 60 per cent of their original C since the beginnings of agriculture, and this loss has been accelerating with the advent of modern agricultural techniques. This crisis also creates a great opportunity -- if we can put a lot of the excess atmospheric C back into the soil, we will help prevent climate change at the same time as we create healthier soil functions – a real win-win scenario.

Nobody denies that this opportunity exists – the question is one of rate – how fast can we sequester carbon? Experts differ on this important question, but some recent science appears to be telling us that the use of soil-health methods can sequester C at a higher rate than had previously been thought. As an example, a research group in California demonstrated rates of sequestration that were double the maximum rates proposed by the IPCC, simply by applying municipal-waste compost to rangelands. This higher potential sequestration rate appears to be based on the concept that most carbon sequestered in soil is the result of activities of the soil food web, and that it remains in soil longer than previously proposed because it is physically protected from degradation inside the aggregates.

The science on this topic is still evolving and not yet well established. However, it does appear possible, at the very least, that the proponents of high rates of soil-carbon sequestration may well be correct. If so, this is good news for both farmers and the environment.