Soil carbon sequestration – myths and mysteries

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Introduction

The balance between carbon (C) sequestration (or storage) in various sinks such as soils and vegetation and that released to the atmosphere as carbon dioxide (CO_2) is topical, given the global warming/climate change projections. However, there is a considerable degree of uncertainty surrounding what options are available, how realistic they are and, more specifically (from a soil perspective), what role does soil C play in mitigating the effects of CO_2 emissions. This paper tries to place soil C in a global perspective and to assess how realistic it is for significant soil C sequestration to occur in different land use systems. In order to do that, we need to provide some background on soil organic matter, the main soil C pool which can be influenced through land management. This will consider the different forms of organic C in soil, how they can be measured and the role they play in determining soil functions and properties.

Soil as a carbon sink

Carbon stored in soils world-wide represents the third largest sink in existence, after oceans and geologic sinks, representing 2–4 times the C in the atmosphere, and about 4 times the C stored in vegetative material (plants). It is therefore understandable that soil C is being viewed as a sink that could potentially have a significant impact on sequestering CO_2 emissions. However, before we consider how feasible it is to store extra C

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in soil, it is essential to understand the forms in which soil C exists.

Soil C is found in either inorganic (mineral) or organic forms. Inorganic soil C is generally found as carbonates of calcium ($CaCO_3$—limestone) and magnesium ($MgCO_3$). Excluding concentrated deposits of these materials that arose from deposition of the shells of aquatic invertebrates, most of these inorganic forms of C are found in alkaline soils, with local examples being the heavy clay soils of inland Queensland and northern New South Wales. Calcium carbonate is effectively insoluble in water at pH>8.3; thus, when these extreme conditions are met (typically in subsoils of the black and grey cracking clays), $CaCO_3$ precipitates out of the soil solution to form whitish nodules embedded in the clay soil. While these inorganic forms of C can represent a significant amount of the C stored in the profile of these particular soils in some areas, much more carbon is found in the organic form.

The organic forms of C in soil are a diverse group of materials that can be defined as 'everything in or on the soil that is of biological origin—whether it's alive or dead'. It therefore includes live plant roots and litter (not shoots), humus, charcoal and other recalcitrant residues of organic matter decomposition. It also includes the organisms living in the soil that are collectively called the soil biota (including fungi, bacteria, mites, earthworms, ants and centipedes). The one factor that all these materials have in common is that they contain C, and so you will generally hear talk of the interchangability of soil organic matter and soil organic C. On average, organic matter in soil contains about 60% C; thus, if a test shows 1% organic C, the soil will contain about 1.7% (by weight) organic matter.

Forms of organic matter and C in soil

Soil organic matter is ultimately derived from decomposing plant material, with that decom-

position driven by the soil biota for which the plant material and decomposition products are the primary source of energy and nutrients. In the process of this decomposition, populations of different components of the biota wax and wane in response to the abundance of their preferred food source, and to their predation by other organisms. Similarly, the abundance and age of different components of soil organic matter fluctuate in response to the quality and quantity of inputs (*i.e.*, residue type and frequency of addition) and the influence of moisture and temperature on the decomposing organisms.
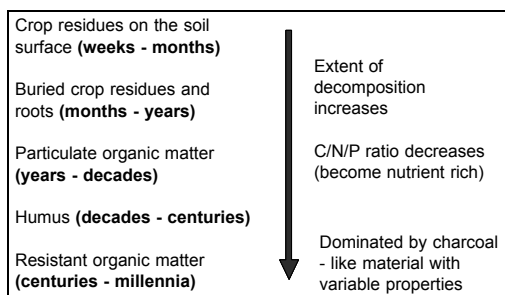

The principal components of the non-living soil organic matter pool are shown in the schematic above, along with an indication of the 'half-lives' for material to progress from one pool to another. Obviously, this time varies with environmental conditions, such as temperature and available moisture that influence microbial activity, with the decomposition process slowed enormously by cold temperatures (*e.g.* on North American prairies or Russian steppes) and low annual rainfall. This time-scale is useful for thinking about both the decline in soil organic matter that occurs under exploitative land uses and also the time to replenish soil organic matter stocks (especially the more stable compounds like humus) under natural conditions.

Fate of C and nutrients during transformations

As the microbial decomposition process occurs, C and some nutrients are liberated. The C is released as carbon dioxide (or methane under certain conditions) from microbial respiration, and surplus nutrients are released (mineralised) in inorganic forms suitable for use by other microbes and plants.

However, soils are generally nutrient-poor environments so, as the decomposition process occurs and the organic materials age in the soil,

there is generally more C released as CO_2 than there are surplus nutrients released (*i.e.*, a fungus needs 8 C atoms for every N atom to grow more hyphal threads, but can digest poor-quality crop residue with a C:N ratio that starts at 100:1). As a result, surplus C is respired, while the N is conserved, and through the aging process in soil the organic materials become increasingly nutrient rich. This enrichment of nutrients in humus and more recalcitrant, charcoal-like materials occurs particularly with N and sulphur (S). The humus that eventually forms from decomposition of, say, cereal straw will have a C:N ratio of approximately 12:1, rather than the 100:1 in its original form. After so many cycles of digestion and excretion these materials are less readily decomposed than when they entered the soil as plant residue, but the nutrients they contain ensure that they remain a valuable source of nutrients contributing to soil fertility.
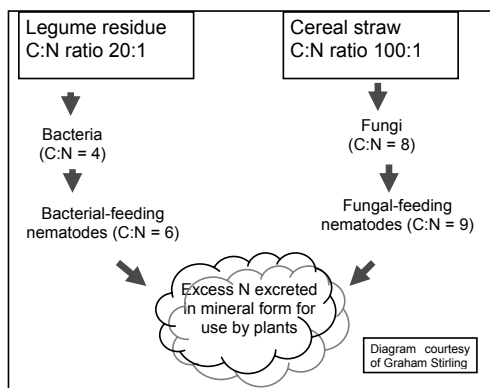
A good example of biological nutrient cycling and release for plant utilisation is shown in relation to N in the above diagram. Bacteria or fungi growing on plant residues are preyed on by a number of more complex organisms such as free-living nematodes, which typically have higher C:N ratios than the organisms on which they feed. The excess N in this case will be released in an inorganic form (either ammonium-N or nitrate-N) for use by plants or other organisms. This inorganic N can build up as decomposition continues (if it is surplus to requirements of the microbial community) and will form the basis of the N supplied to the next crop. The lower the C:N ratio of the material being decomposed (*i.e.*, humus *vs* fresh cereal straw) the more likely there is to be net release of mineral N.

The converse of this is that, if we want to raise soil organic C levels by increasing soil organic matter (rather than adding a relatively inert mate-

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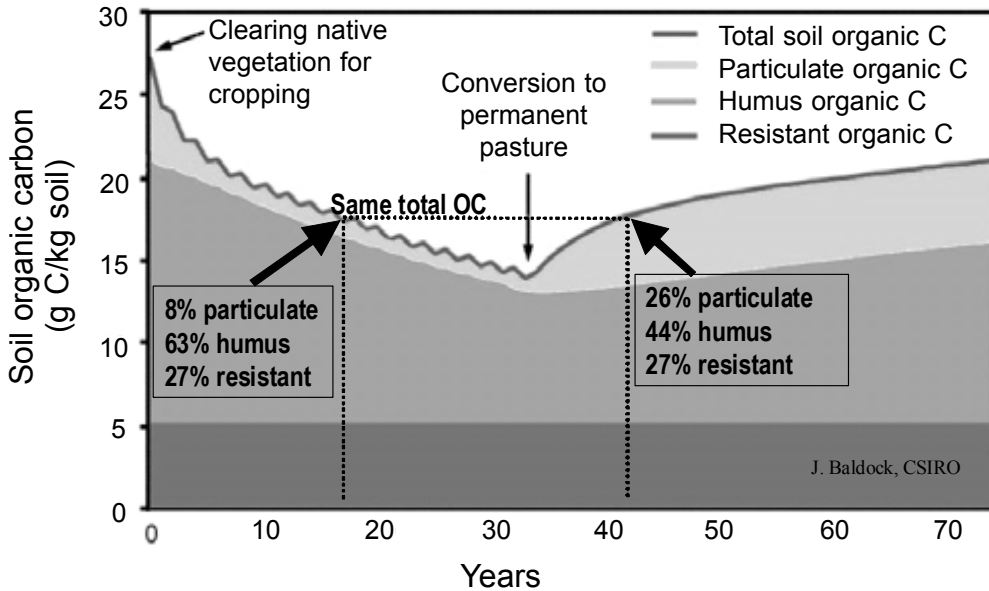
rial like coal dust, for example), we will be tying up nutrients. As an example, for an increase in soil organic C content of 1% (*e.g.* from soil C of 1% to 2%) to occur, 900–1500 kg/ha N and 70–120 kg/ha P must be available to form that organic matter. If the soil has a low fertility status (*e.g.* is run down in N), then soil organic matter cannot increase unless the N is provided (as from a legume-based pasture). Similarly, increases in soil organic matter levels in soils with low P status will be limited unless the P deficiency is overcome, just as legumes will struggle to persist in pastures and fix N. Understanding these concepts is important to provide a realistic perspective on what is achievable and at what cost in the soil C sequestration debate.

Relative sizes of the different C pools

The size of the overall C pool in soils can be misleading as an indicator of how that soil will behave unless we understand something about the relative proportions of the different 'pools' in which that C can be found. For example, soils that have differing proportions of soil as particulate organic matter (relatively young, labile material), humus and recalcitrant compounds like charcoal, will behave very differently—both in terms of properties and the microbial communities (and resulting functions) they can support. Soils supporting open grasslands will have pro-

portionally more char-like material in their native condition (from regular natural fires) than similar soil types under a rainforest, for example. Similarly, soils growing sugar cane in areas where trash is burned regularly can also have a higher proportion (up to 50%) of soil C as charcoal -much higher than where there has been a history of trash blanketing.

These proportions are important. Consider the soils shown in the following example (adapted from Baldock and Skjemstad 1999), where soil is examined on 2 occasions in its management history – once during the continuous cropping phase and again after further cropping and then an 8–10-year period under pasture. If simply analysed for total organic C, both soils would appear similar. The amount of resistant/char-like material is unchanged (remember – a half-life of centuries). However, while there has been a large increase in the particulate/labile fraction in response to the pasture, the amount of humus (decades-centuries to form) is much lower and still reflects the end of the cropping rundown period. This means that: (i) the long-term soil nutrient stores have not recovered; and (ii) this soil organic matter will decline much more rapidly if the land is returned to cropping. In fact, the original rate of soil organic matter decline would effectively double in the next cropping phase, and much more frequent pasture phases would be needed to maintain soil productivity. While this is a hypothetical example

from simulation studies, we have observed the rapid decline in soil organic matter after pasture leys in our own trials in the inland Burnett region of Queensland.

Soil C measurement

The commercially available techniques for measuring and monitoring soil C, or more importantly components of the soil C pools, are currently limited. Total soil C measurement, either by combustion or by Heanes wet oxidation, provides realistic measures of total C status. Most routine soil tests report soil organic C measured using the Walkley-Black wet oxidation technique, which measures only 70–90% of the total soil organic C, depending on soil type. Both wet oxidation techniques will measure only the organic C, which is an advantage they have over the combustion methods. This can be particularly important when measuring soil organic C on high pH soils like the Vertosols, where subsoils can contain a lot of inorganic C as $CaCO_3$, and require acid pretreatment before total C analysis using combustion.

None of these techniques can quantify charcoal or other recalcitrant C materials, or the humus or particulate organic matter pools, so they are relatively uninformative in terms of measures of soil C quality. Hopefully, recent developments in infrared spectroscopy will allow a cheap and relatively rapid assessment of the components of the soil organic matter pools.

There has been an explosion of interest in measuring soil biological activity, either by measuring factors such as microbial biomass C or by measuring general or specific enzyme activities that can be attributed to the microbial community (for example, fluorescein diacetate – FDA). However, all of these techniques have limitations in that they are unable to detect changes in microbial diversity. Microbes are also extremely dynamic in response to changing moisture and temperature conditions, as well as the availability of food sources (whether sampled in a fallow, during a crop or just after tillage). While there is much interest in using molecular techniques to measure changes in soil microbial diversity, there is much work to be done before these techniques are available and measures of diversity can be linked to soil health and functionality.
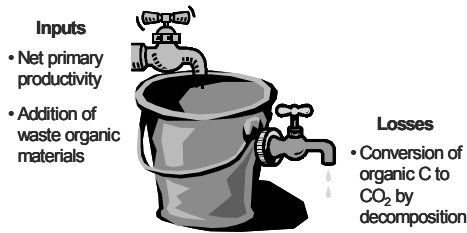
Why does soil C decline?

Soil organic C represents an equilibrium condition reflecting the balance between C inputs (such as residues and roots) and C mineralisation and loss as CO_2—for a given climate and soil type. We often hear about declining soil organic matter and C stores in cropland because the change from a native pasture or woodland to cropping has meant a relative reduction in C inputs and an increase in carbon removed in harvested products and by gaseous loss. The result is a slow shift towards a new (lower soil C) equilibrium position. This changed position will reflect a new balance between inputs and losses and, particularly under rainfed cropping conditions (even under the best conservation tillage techniques), will be significantly lower than under native vegetation or grassland. This is logical, because where native vegetation or pastures use every available drop of moisture to grow biomass and fix atmospheric C all year round, there are periods (quite long in recent years) where crops are not growing while soil moisture is recharged, but microbes are still decomposing soil organic matter. Moreover, the disturbance associated with tillage accelerates the rate of organic matter and residue decomposition, primarily by making more of the organic matter available to soil microbes for breakdown.

How can soil C be restored?

If we wish to change soil organic C status, presumably in order to improve soil health and the productivity/profitability of the enterprise, there has to be a shift in the balance between inputs and losses (see diagram). In other words, we have to increase the inputs while minimising losses. This looks simple, but can become quite complicated when economic imperatives and climatic limitations are added to the equation.

Increases in C inputs can generally be achieved by increasing productivity (more biomass grown generally = more residues returned) and, to a lesser extent, by using soil organic amendments if available (although this means that C is being removed from its site of origin). However, it is worth considering the size of the C pool to get some perspective on the use of either strategy, but particularly that of organic amendments. A black cracking clay with 1% organic C will contain approximately 10 t/ha C in the top 10 cm layer, while a 5 t/ha grain sorghum crop will return approximately 10 t/ha organic matter as roots and surface residues (about 4 t/ha C). Contrast that with applying 5 t/ha of feedlot manure (say 30% C) once every 5 years or so, and you can understand why soils which have been strate-

Inputs
• Net primary productivity
• Addition of waste organic materials

Losses
• Conversion of organic C to CO_2 by decomposition

gically manured often have similar soil organic C to those which have not.

Perhaps the most effective strategy is to grow something in the soil as often as possible (*e.g.* opportunity cropping, possibly including green manure cropping, or converting land from annual cropping to pastures—with perennial grasses being more effective than annual) to make best use of the available moisture to grow biomass. Of course, the economics of that will be determined by how much you are paid to grow that biomass, or can make from a grazing enterprise versus cropping.

Reducing losses presents a conundrum as many of the functions of a healthy soil are provided by microbial activity during organic matter decomposition. In other words, we want to control the rate of decomposition, perhaps better matching that rate to the soil type and climate, rather than stopping decomposition and CO_2 emissions altogether. Good examples from cropping include retaining crop residues in the soil by eliminating burning and reducing tillage, while the equivalent in grazing systems would involve optimising grazing pressures through manipulating stocking rates. Again, combinations of economic pressures and climatic sequences will have a big impact on the practicality and effectiveness of these strategies.

An interesting approach gaining publicity at present lies in the conversion of organic wastes and crop residues into relatively inert C compounds by pyrolysis to create biochar, and then adding this to soil. While economics will ultimately decide the feasibility of this strategy, it is worth remembering that inert materials like biochar have long residence times in soil because they are relatively recalcitrant to soil microbial decomposition. This may make them attractive to proponents of char as a way of sequestering C in soils, but at what cost? All that biological nutrient cycling, building of soil structure and disease suppression that are characteristic of a healthy soil could be compromised by converting what are already scarce resources in soil (organic

matter inputs) into more expensive and relatively inert organic matter inputs. Amendments like biochar (which needs to be produced under carefully controlled pyrolysis conditions—'chars ain't chars') can provide other benefits (such as immobilising toxic aluminium in acidic soils), but the impact of these benefits is restricted to some 'special case' combinations of soil types and climate and should not be extrapolated across all agricultural soils.

Conclusions and practicalities

Organic C and organic matter are the keys to healthy soils that are able to support productive and sustainable land uses—in both agricultural and natural ecosystems. As we have discussed previously, it is dangerous to consider soil and soil organic matter simply as a potential sink for impounding excess CO_2. As Janzen (2006) described, 'soil organic matter effectively constitutes a relentless flow of carbon atoms moving through a myriad of streams—some fast and some slow—wending their way through ecosystems and driving biotic processes along the way'. In other words, it is the flow of C *through* soils, rather than its sequestration *in* soils, that is the key to healthy soils and sustainable land use systems. We therefore will gain greatest benefits from increasing the inputs of carbon and organic matter to soils by growing better crops and pastures more often. There is no doubt that equilibrium soil C contents can be increased by combinations of practice change and land use, but the extent to which this can contribute to reducing the rate of increase in atmospheric CO_2 is unclear and will ultimately be determined by imperatives of global food supply. In the interim, producers should remember that, within a given land use, the systems that result in the greatest productivity (and often the most efficient use of scarce resources to grow biomass) will ultimately have the greatest benefits for soil C and soil health.

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