

Soil Carbon

The legacy of the past and the powerhouse of the future

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Abstract

A review of the decline in soil carbon and its effect on crop yields, soil health and the health and wellbeing of the farming family over the last thirty years, suggests that many have been worshipping the wrong sacred cow and need to change the focus to achieve a more sustainable triple bottom line.

The paper reviews the historic loss of 50-60% of soil carbon and its effects on the physical, chemical and biological aspects of soil health. Farming practices that influence these soil carbon losses and the methods and principles of increasing the carbon sink in the soil are discussed.

The importance of root exudates in maintaining a balanced soil food web, nutrient cycling, soil health and disease suppression are illustrated. The newly discovered soil 'super glue' glomalin maintains up to one third of the carbon in the soil for between 7-40 years. This provides evidence of the benefits of mycorrhizae.

It is suggested that the trophic diversity of nematodes, measurements of glomalin and mycorrhizal colonisation could be considered useful tools in monitoring the soil health.

The paper serves to illustrate the need to adopt farming practices such as reduced fallow, stubble retention, no-til farming, pasture-cropping, crop rotations, cell-grazing and other practices that increase the three soil carbon pools.

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Introduction

Many will recall your earliest introductions to agriculture and the importance of organic matter, which is basically made up of soil organic carbon.

Almost seventy years ago in the 1938 USDA Yearbook of Agriculture *Soil and Men*, William Albrecht wrote a chapter entitled '*Loss of Soil Organic Matter and its Restoration*'. Albrecht tells why soil organic matter is our most valuable natural resource and speculates that we should at the very least maintain the levels of soil organic matter (Kimble 2001).

Mother Nature must get very discouraged at how slow we are to learn from the legacies of the past. Even though we have long understood the importance of maintaining soil carbon, we continue to use land management practices that deplete the essential element of all life on Earth at an exponential rate. It is hard to visualise today that 4,000-5,000 years ago in what is now Iraq and Saudi Arabia, cities thrived and were surrounded by irrigation and intensive agriculture (Nova: Science in the news 2006 online). Our history is littered with similar illustrations of civilisations that used non-sustainable farming methods.

We must admit we are indeed slow learners. With all the knowledge we have at our disposal today we continue to use and abuse this life-giving resource along with our precious water. In Saudi Arabia for instance, deserts have replaced high carbon soils and the valuable underground liquid carbon is rapidly being exploited along with the ancient aquifers. The ancient aquifers are being sucked dry at an alarming rate, by thousands of centre pivots, to grow wheat at cost of approximately US\$480/t. It is anticipated that due to the lack of recharge, these 4000-year-old aquifers will run dry over the next 20 years. At the same time 1500 million cubic metres of effluent water are generated each year, most of which is discharged into the sea (Ishaq & Mahsood 2000).

The triple bottom line

Sustainability is a simple concept, but in reality it is a complex mosaic of competing issues. The idealistic approach is the concept of the triple bottom line.

Getting the balance right on the farm revolves around the balance of the farm (environment), the bank (economy) and the family (social). The reason for raising this concept is that when we consider our

record on soil carbon depletion, soil health and the health and well-being of the family over the last twenty to thirty years, it is obvious that many of us have been worshiping the wrong sacred cow and we need to change our focus. Our focus on higher gross margins per hectare, tonnes/hectare, cows/hectare or milk production per cow maybe the wrong benchmarks. Maybe we should be looking for a better way to measure the health and wellbeing of the soil, the water and the family.

Conventional wisdom has generally promoted a quick-fix easy solution. For example as yields have declined along with organic carbon, we have added more urea, more water, or grown plants that are less demanding.

Organic or truly sustainable farming practices do not always result in the highest output or present the neatest, cleanest farms, but I suggest that they frequently provide the greatest feelings of satisfaction.

Let us look briefly at a few examples in the past, when the focus on the Triple Bottom Line was somewhat blurred.

The 'Green Revolution'

During the excitement of the 'Asian Green Revolution' in the early 1970's, the Indonesian government persuaded Balinese farmers to adopt new fertilisers, pesticides and cultivate 'miracle' rice in a \$54 million scheme of modernisation. They were encouraged to give-up their ancient traditions based on a combination of complex religious, social and technical processes focused on the Water temples. Water temples were the heart of village life and irrigated rice terraces have been the economic mainstay of most Balinese villages for over 1000 years. This tradition optimised water sharing among hundreds of farming communities, kept pest levels at a minimum and successfully grew rice and other crops on the brilliantly, stepped wet-rice terraces of southern Bali. Farmers were pressured to triple plant the new 'miracle' rice as frequently as possible and to adopt new methods. By 1971, about 70% of the terraces were planted to the miracle rice. At the same time the Asian Development Bank began a major irrigation development project.

By 1974 field officers were reporting 'chaos in water scheduling' and 'explosions of rice pests'. Soon rice production began to decline due to water shortages and increased pest pressure. The soil also became harder to plough. Reports on the problems by Dr Stephen Lansing to the vice-president of the Asian Development Bank in 1984 were ignored and the Bank continued to advocate the use of pesticides. Four years later a World Bank study reported that the use of pesticides had *'pervasively polluted the island's soil and water resources.'*

By 1989 the Balinese had changed back to the Water Temple regulated system and today they are still dealing with soil and ground water contamination. As Dr Lansing puts it, *'These ancient traditions have wisdom we can learn from'*. His message resonates well beyond the rice paddies of Bali.

It illustrates the value of an anthropological, holistic approach to ecological and agronomic problems around us today (Lansing 1991).

The Brigalow soils

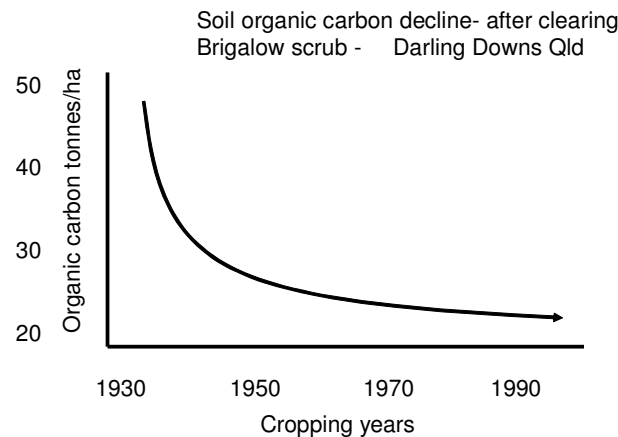
Closer to home in our 'Lucky Country' and in our time, we are witnessing the continued exploitation of soil organic carbon. Throughout Australian cropping lands, soil fertility continues to decline along with crop yields (Fig. 1).

In Queensland, grain yields have remained stagnant (mean 1.4 t/ha) over the last thirty years despite nitrogen fertiliser usage increasing by about 300%, improved varieties and management practices. The soil organic carbon levels have declined by 30-60%. Soil erosion was not a problem on this land so that most of the loss was as carbon dioxide, contributing approximately 88 t/ha of carbon dioxide to the atmosphere, increasing greenhouse gas emissions. This decline in organic carbon is typical of cropping lands everywhere. The only difference being that this heavy clay soil originally grew 'Brigalow', a leguminous scrub which continued to yield good crops longer than most soils.

Soil organic carbon data from all around the world suggests that 50-60% of soil organic carbon is lost in the first 3-15 years of cropping, where the rate of decline is influenced by factors such as clay content, rainfall and cropping history.

Taking a positive look at the historic loss of 50-60% of the soil organic carbon, the good news is that we now have space to store the new carbon, because under the original natural ecosystem the high levels of carbon were at a relative equilibrium.

This carbon forum is intended to inspire and renew our commitment and increase our understanding of the role of soil carbon and consider ways to reverse this decline.



Source: Dalal et al, 2003

Figure 1. Modelled decline in soil organic carbon since 1935 after land under brigalow was cleared for cereal cropping on the Darling Downs (after Dalal 2003 cited by State of the Environment Queensland online).

The way it all works

Increasing soil carbon on the farm will improve productivity and sustainability and off the farm we can look forward to improved water and air quality. The way this all works is through photosynthesis, the plants converting carbon dioxide from the atmosphere into organic forms of carbon. In nature, the plant returns this carbon to the soil as root exudates or as decaying plant material. Soil organic matter is at the core of all the major constraints to plant growth and impacts on soil quality and function. These can be divided into physical, chemical and biological factors.

Physical effects:

- soil aggregation
- erosion
- drainage
- aeration
- water-holding capacity
- bulk density
- evaporation
- permeability

Chemical effects:

- cation exchange capacity
- metal complexing
- buffering capacity
- supply and availability of N, P, S and micronutrients
- absorption of pesticides and other added chemicals

Biological effects:

- provides the energy, nutrients and protection for the soil food web

Soil Carbon: long term effects of crop rotations

Long term research shows that intensive cultivation and a lack of diverse crop rotations results in a decline in soil organic carbon (Fig. 2).

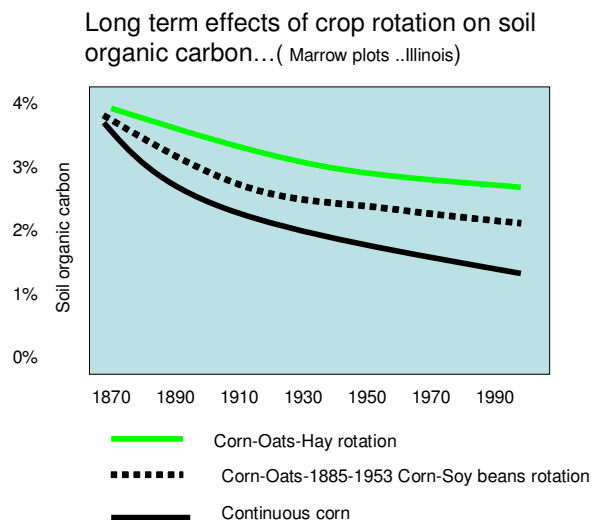


Figure 2. Shows long-term effects of crop rotation on soil organic carbon in Illinois, USA.

There is a misconception that conventional cultivation coupled with high fertiliser use can increase soil organic matter and hence soil carbon. This is not necessarily the case for the following reasons:

- Cultivation causes oxidation or burning of soil organic matter, releasing carbon dioxide.
- Adding more fertilisers increases yield and crop residue but when incorporated by ploughing or chiseling, it decomposes using up stored carbon from last season, resulting in a net loss of soil carbon.
- The incorporation of residue cover followed by bare soil increases the risks of a loss of soil organic carbon from erosion (Al-Kaisi & Reicovsky 2002 online).

Soil Carbon: soil salinity/sodicity

When salinity and sodicity increase, plant growth decreases and the microbial population increase due to the reduced competition for nutrients. Soil organic carbon is further depleted by the flourishing microbes and more soil carbon is lost and plant biomass decreases. The effect on carbon is like a snowball rolling down a hill and the problem continues to worsen (Wong *et al.* 2004).

Soil Carbon: primer plants in crop rotations

The use of primer plants such as lucerne in crop rotation can push down transient salinity/sodicity in the profile and in so doing increases soil carbon and crop yield.

Carbon loss: choice of tillage equipment

The choice of tillage equipment has an impact on the loss of carbon from the soil as carbon dioxide (Fig. 3).

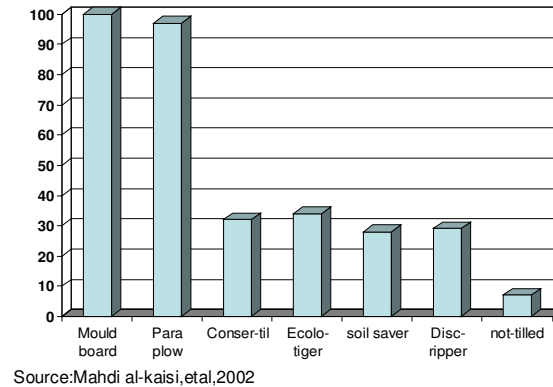


Figure 3. Shows the variation in loss of carbon as CO₂ when using different types of tillage equipment (from Al-Kaisi & Reicovsky 2002).

Carbon degradability: crop residue

Understanding the carbon degradability of crop residues and other carbon amendments will help us to manage soils to increase soil carbon (Fig. 4, Table 1).

| Stubble nutrients and losses from a hot burn (5t/ha crop-7.5t/ha stubble) | | |
|---|--------------|--------|
| | Nutrients | Amount |
| Nutrients in stubble (kg/ha) | N | 56 |
| | P | 5.9 |
| | K | 109 |
| | C | 3450 |
| Nutrients losses during burn | N | 46 |
| | P | 2.6 |
| | K | 44 |
| | C | 2760 |
| Percentage lost | N | 82% |
| | P | 44% |
| | K | 40% |
| | C | 80% |
| Fertilizer equivalent lost in burn (kg/ha) | Urea | 100 |
| | Super | 30 |
| | MoP | 87 |

Figure 4. Carbon loss: burning crop residue.

Table 1. Some differences in carbon degradability of crop residues and other carbon amendments given for some carbon sources.

| Carbon source | Carbon % | Total C/N | Degradable Carbon % | Degradable C/N | Nitrogen % |
|----------------|----------|-----------|---------------------|----------------|------------|
| Newspaper | 39.3 | 115.5 | 18.4 | 54.1 | 0.34 |
| Wheat straw | 51.1 | 88.7 | 33.6 | 58.0 | 0.58 |
| Poultry manure | 43.1 | 9.6 | 41.8 | 9.3 | 4.51 |
| Wood chips | 49.7 | 51.2 | 43.8 | 45.1 | 0.97 |

The ideal for composting is a C/N ratio of 25-30:1, the C/N of wheat stubble is 58, therefore, to balance the high carbon, nitrogen is required from the soil or fertiliser. Every tonne of wheat stubble will require about 5 kg of Nitrogen (10 kg of urea) to provide a C/N ratio of 30. By calculation, a 5t crop of wheat having 7.5 t/ha of stubble will require 38 kg of nitrogen/hectare. A source of readily available carbon such as molasses at around 0.5% (5 kg/t) of stubble under favourable conditions should accelerate the rate of break down (Fig. 5).

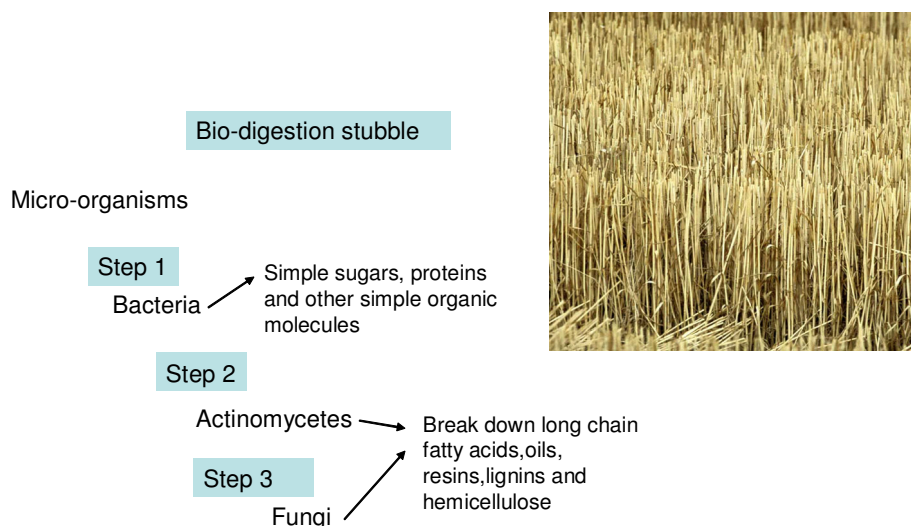


Figure 5. Bio-Digestion of crop residues.

Soil Carbon: role in the rhizosphere

Soil carbon provides the energy to sustain biological activity, diversity and productivity, regulates and aids nutrient and water movement, detoxifies and degrades organic and inorganic products and acts as a sink for storing and recycling nutrients.

The rhizosphere is the absorbing root-soil interface. It is the zone, about one millimetre in width, surrounding the root hairs and mycorrhizae and hyphae.

The rhizoplane is the boundary where soil nutrients in water are absorbed into the plant. Under an electron microscope, the rhizoplane appears as a jelly where microorganisms and plant cells mix, making it almost impossible to tell which is plant and which is soil.

The soil food web is a constantly changing mix of organisms that inhabit the rhizosphere and surrounding soil. Bacteria, actinomycetes, fungi, protozoa, slime moulds, algae, nematodes, earthworms, millipedes, centipedes, insects, mites, snails, small animals and soil viruses compete constantly for water, carbon, nutrients and space.

The rhizosphere is a battleground and the wars are continuous. Amoebae are eating bacteria. Some bacteria are poisoning other bacteria. Fungi are killing other fungi. Nematodes are spearing roots. Fungi are trapping nematodes. Earthworms are eating anything they can find.

Troubles in the rhizosphere

When there are troubles in the rhizosphere, there will be troubles with the crop/tree (Shigo 1996 online). Every plant management action affects the rhizosphere in some way. The more you know about the rhizosphere, the better the chances are that your land management will lead to benefits rather than harm. It is often very difficult to have people recognise the importance of small organisms in small places doing big things.

Soil compaction

For instance, consider the effect of soil compaction in the rhizosphere. In healthy soil fungal hyphae may make-up to 40% of the dry weight of roots and when fungal hyphae die and are digested, they leave tunnels in the soil that are about 3-10 microns in diameter. For the bacteria, these small tunnels may mean the difference between life and death. The bacteria quickly colonize the tunnels. The survival advantage here is that the major threats to their survival are protozoa that are usually much larger than 10 microns. So the hungry amoebae are not able to get at the bacteria inside the seven-micron tunnels.

A common treatment for compaction is to fracture the soil by ripping and add water. The fracturing allows air to penetrate the soil, which allows more carbon to oxidize and escape and it does not provide any seven-micron tunnels for the bacteria. The only way to bring back the tunnels is to bring back the fungi. Cultivation easily destroys the soil fungal networks and the soil quickly becomes bacterial dominant. Bacteria convert more plant carbon into carbon dioxide, while fungi tend to retain more carbon in the soil in various microbial carbon products.

Glomalin, the carbon based 'Super Glue'

One such product, recently discovered and named by ARS soil scientist Sara Wright (2002 online), is 'glomalin' the soil's 'super glue'; a glycoprotein containing up to 30-40% carbon made by mycorrhizal fungi. It has been suggested that glomalin is the hiding place for one third of the World's stored soil carbon, so much so that it maybe the most suitable single carbon measurement for future soil carbon accounting. A study at the University of Maryland showed that glomalin accounted for 27% of the carbon in soil and is a major component of soil organic matter. Carbon dating also revealed that glomalin may last in the soil for 7-42 years depending on conditions.

A four year study by Wright (2002) found that under 'no-till' cultivation, glomalin increased each year, rising from 1.3 mg/g to 1.7mg/g in 3 years, while nearby a field ploughed and planted each year had only 0.7 mg/g, while the grass buffer strip had 2.7 mg/g. Levels elsewhere have been as high as 100mg/g.

It would be wise that all future research measuring the sequestering of carbon in the soil include the accumulation of glomalin and mycorrhizal colonisation over time.

Plant exudates in the rhizosphere

Of the total dry matter production of organic carbon from photosynthesis, 5% to 40% may be released as root exudates!

The amount of organic carbon released as exudates increases when a plant stresses. Over-pruning, over-grazing, mechanical damage, planting too deeply, over-watering, compaction or planting in soils that have a pH too high or too low for their optimal growth may cause this. Exudates contain carbohydrates (carbon), organic acids, vitamins and many other substances essential for life.

Small events often lead to a decrease in a plant's defence system. Then after the tree/crop has been weakened, the final agent comes along and gets the full blame for the cause. Most pathogens are really opportunistic weaklings waiting for the defence system to weaken. The blame for the death of a tree or a failing crop is then often placed on big things that can be seen or felt. It is very difficult to

determine where problems start in an oscillating pump. Symptoms may be in the bottom, but the cause may have been in the top. Or it could be the other way around. Leaves and photosynthesis provide the energy at the top of the pump. The non-woody roots and the rhizosphere provide the nutrients and water at the bottom. Photosynthesis will not work without water and nutrients and the absorption processes will not work without an energy (carbon) source.

Exudates provide quick energy (carbon) for the rhizosphere organisms, while plant roots and tops provide a longer-lasting energy source for the microorganisms.

Carbon and nutrient availability

The organisms in the rhizosphere and surrounding soils have many different ways to weather rocks and to get nitrogen and other nutrients essential for their growth. What they cannot get from the soil is sufficient energy (carbon). Energy must come from the top of the plant. When the energy source from the top begins to decrease, the rhizosphere organisms begin to starve.

Understanding nutrient cycling in the rhizosphere maybe easier to visualise, if we relate it to a cow grazing in a nutritious pasture, where the excess nitrogen is excreted as urine, which in turn increases the nitrogen in the soil and grows more grass.

In a similar way but more efficient (microbes don't have a liver), a grazing protozoa with a C/N ratio of 30 has to eat six nitrogen rich bacteria with a C/N of 5, to satisfy its carbon needs. Then having consumed too much nitrogen, the protozoa 'excrete' the 5 nitrogen not required into the soil (Fig. 6). Repeated billions of times, we can visualise how a tropical rainforest gets the +400 kg of nitrogen per hectare.

Plants can modify the organic acids in their exudates that make complex nutrients such as aluminum and iron phosphates available to the plant. They can also alter the supply of energy to mycorrhizal fungi and soil bacteria. For instance if there are high levels of water soluble phosphate, the plant can shut down supply of carbohydrates to the mycorrhizae, causing them to slough off and die.

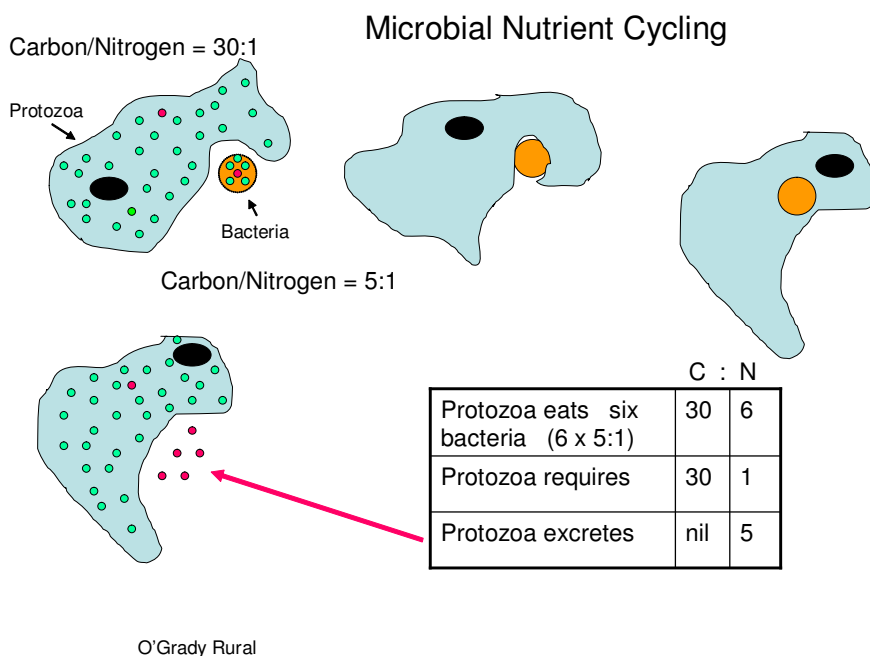


Figure 6. Grazing protozoa with a C/N ratio of 30 has to eat six nitrogen rich bacteria with a C/N ratio of five to satisfy its carbon needs.

Carbon in disease suppression

Virgin soils have a natural bio-diversity and balance and are relatively free of crop diseases. While crop pathogens will be present they are held in check by the bio-diversity of the soil (McSpadden Gardener & Farvel 2002). The mechanisms that maintain this healthy soil include competition for nutrients and space, antibiosis – the production of an antibiotic or toxic compounds, parasitism and induced systemic resistance, where substances called elicitors trigger off a plant response that increases its resistance to disease.

Crop diseases usually start to appear when this natural environment is altered by loss of carbon, cultivation, chemicals and or the introduction of new pathogens on equipment or planting material. Diseases can be suppressed when these natural mechanisms are understood and farm management practices are modified to enhance a soil's bio-diversity. Farming practices such as reduced fallow, stubble retention, no-till farming, pasture-crop farming, crop rotations, returning marginal lands to pastures or trees, cell-grazing, planting of shelter belts and establishment of wetlands will all increase the amount of carbon stored and the soil's bio-diversity and increase disease suppression.

One of the better bio-indicators of soil health is to measure the trophic diversity of nematodes in the soil. Nematodes are at the centre of the soil food web and are relatively stable under varying environmental conditions. Soil nematodes are recorded by their feeding group (trophic diversity) as bacterial feeders, fungal feeders, plant feeders, switchers and insect feeders. In an old cultivation for instance, there will be no fungal feeders if there is no fungi in the soil.

Carbon pools

With our knowledge of the complexity of soil carbon, we can no longer just consider total soil carbon, we need to look at the three carbon pools in the soil:

1. the labile pool with a turnover rate of less than a year (e.g. substrate nutrients);
2. the intermediate pool which has a turnover rate of 1-100 year (e.g. glomalin);
3. the stable pool with turnover rate of 100-1000+ years. (e.g. charcoal).

In order to create a stable environment we need to focus more on the intermediate and stable pools. Up until recent times the importance of the stable carbon pool has had little attention, apart from its potential to provide a soil 'sink' for carbon.

In fact, in the CSIRO media release 97/58 (3 April 1997) 'Legacy of a Thousand Bushfires', the comment was made that 'Much of our small supply of carbon – an essential element in fertile soils – is in the form of **useless charcoal** resulting from tens of thousands of years of bushfires'. Our rapidly expanding knowledge of the Terra Preta phenomena is changing this view.

Over the next two days speakers will discuss how it is possible to manage lands to reverse this carbon loss and maximise carbon storage in the soil 'sink'. The farming choice is simple:

- continue using conventional wisdom; or
- accept the challenge towards creating a 'carbon sink' on the farm.

The choice is yours.

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