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# carbon in soils

**Soils store substantial amounts of carbon (C) in soil organic matter, and the amounts are an important component in the global C cycle as *Graham Sparling and Louis Schipper, Department of Earth and Ocean Sciences, University of Waikato* describe:**

## Carbon in the Earth's rocks, oceans, atmosphere and soil

Carbon is the fourth most common element in the galaxy (by mass) but does not even rank in the twelve most abundant elements on Earth. By far the most abundant source of carbon on Earth is in the crust as *inorganic* rocks such as calcite and limestone in marine and sedimentary deposits. These rocks have taken many millions of years to form. Other major inorganic sources are in the oceans and atmosphere.

Carbon is also a major and essential constituent of living creatures, and is present in *organic* forms, but the amount present as living plants and animals or as dead plants and animals (litter, organic matter and fossil fuel deposits) is small compared to that in rocks (Table 1). The organic forms of carbon in soil are often referred to collectively as soil organic matter, humus, or soil carbon. In fact soil organic matter is about 60% carbon, and comprises the largest terrestrial store for organic C, more than in living plants and animals.

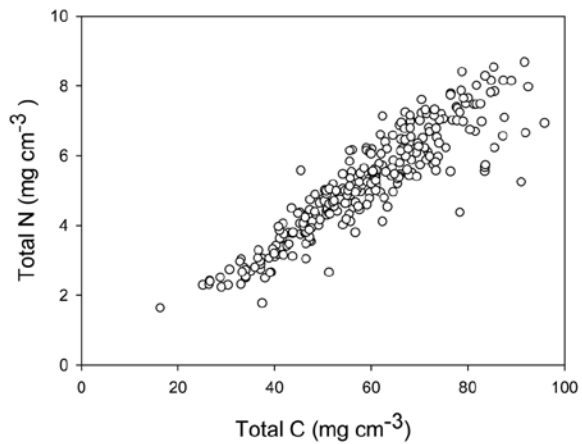
Store	Amount in Billions of Metric Tonnes
Marine Sediments & Sedimentary Rocks	66,000,000 to 100,000,000
Ocean	38,000 to 40,000
Fossil Fuel Deposits	4000
Soil Organic Matter	1500 to 1600
Atmosphere	578 (as of 1700) to 766 (as of 1999)
Terrestrial Plants	540 to 610

Ref: The Encyclopedia of Earth. [http://www.eoearth.org/article/Carbon\\_cycle](http://www.eoearth.org/article/Carbon_cycle)

## Benefits of soil organic matter

The presence of organic matter C in soils alters the soil characteristics, usually in beneficial ways. Organic matter helps to bind the primary mineral particles, forming crumbs and aggregates. Aggregates help to reduce soil erosion and also give soil its crumbly texture. The crumbly texture makes it easier for plant roots to penetrate and for the soils to drain freely and still retain water. The presence of organic matter helps the soil to store plant nutrients.

Among the most important of these nutrients is nitrogen (N) an essential macronutrient for plants and animals. Mineral rocks contain very little N. Most N in soils has been accumulated through biological processes such as N-fixation by legumes and their symbiotic bacteria, and by chemical inputs from fertilisers and nitrogen oxides in the atmosphere (from lightning forming nitrogen oxides). The ability of a soil to hold onto these sparse N sources is highly dependent on the amount of soil organic C (see Figure 1). When micro-organisms decompose soil organic matter this nitrogen becomes available to plants.

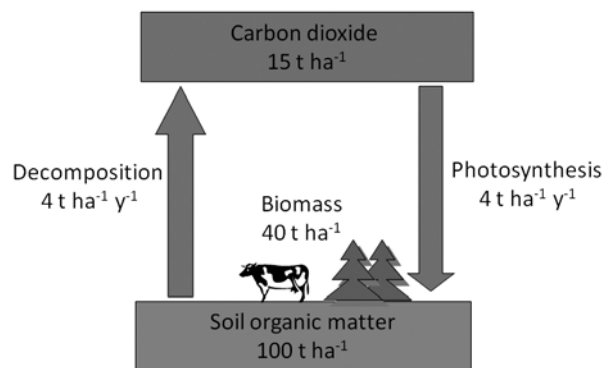


**Figure 1: The amount of nitrogen stored in soil is closely linked to the total carbon content.**

Organic matter has many other beneficial effects for soil, increasing the 'exchange capacity' of soils, which improves the ability of the soil to retain charged molecules such as calcium, magnesium, phosphates, sulphates and trace elements. Soil organic matter also forms both a habitat and food source for soil organisms and is the primary energy store for the soil detritus feeders.

## Living organisms and the source of soil organic matter

Carbon is an essential component of most molecules making up living cells, and responsible for their cell structure, biochemistry, metabolism and genetic code. Carbon enters the biosphere through the photosynthetic ability of plants and some micro-organisms using the energy from sunlight to take carbon dioxide (CO<sub>2</sub>) from air and water and make complex organic polymers and cellular components (Figure 2). In some very unusual environments such as parts of the sea floor or deep underground where light does not penetrate, conversion of carbon dioxide to bio-molecules is driven by the use of chemical energy.



**Figure 2: Average amounts of carbon in one hectare of terrestrial ecosystems and yearly inputs and losses of carbon. (Adapted from Janzen 2004).**

When plants or animals die, the carbon in their cells enters the soil and begins to decay, forming organic matter. The amount of 'dead' organic matter in soil is substantial: three to four times more than in the living terrestrial organisms, but this dead soil organic matter was initially all derived from the 'fixation' of atmospheric CO<sub>2</sub> by photosynthetic organisms. The decay of this organic matter by soil organisms completes the carbon

cycle converting the organic matter to carbon dioxide (Figure 2) and occasionally small amounts of methane.

The living fraction of soil organic matter typically comprises 1–4% by weight of the soil organic C, and is concentrated in the upper layer of soil where the bulk of the organic matter accumulates. The living portion, the soil biomass, is a complex, numerous and very diverse community of bacteria, fungi, protozoa, nematodes and a huge range of microfauna. However, in terms of weight, bacteria and fungi are dominant and comprise about three quarters of the living mass.

### Soil organic matter composition

Soil organic matter is a complex mixture of compounds and differs in composition from soil to soil. As well as C, soil organic matter also contains large amounts of oxygen (O), hydrogen (H), nitrogen (N), smaller amounts of sulphur (S) and phosphorus (P) and a range of trace elements. Derived initially from the decomposing remains of plants, animals and soil microbes, the composition of soil organic matter is not static but is constantly undergoing continuing decay and transformation. It is organic matter that gives topsoil and composts their dark colour.

Various means to characterize soil organic matter have been used over the centuries. Most organic matter is formed of complex aromatic (ring structured) and aliphatic (long chains) of condensed polymers of high molecular weight that are not easily identified.

There is no single structure to soil organic matter because it is derived from a wide range of complex biological compounds, and the organic matter has often been reprocessed many times by soil organisms.

Traditional classifications of organic matter relied on chemical or physical fractionation, for example, soil organic matter has often been separated into fulvic acid, humic acid and humin fractions, depending on its solubility in water, alkali or acid (Table 2). Carbon in the form of charcoal is found in many soils, and is more abundant where there has been regular burning of plant material.

Table 2: Classification of soil organic matter fractions based on their solubility in alkaline and acid extractants			
Group of substance	Solubility in:		
	Water	Alkali	Acid
Fulvic acid	Soluble	Soluble	Soluble
Humic acid	Sparingly	Soluble	Insoluble
Humin	Insoluble	Insoluble	Insoluble

*Adapted from Vaughan and Ord 1985.*

Because strong acids or alkali may modify the organic matter extracted from soil, it is questionable how useful such chemical extracts are, and the extracted fractions still have a very heterogeneous composition. More modern approaches use less drastic methods such as physical separation into 'light' and 'heavy' fractions (using floatation in a high density liquid).

Table 3: Estimates of the amounts and concentrations of soil organic C under different land uses summed for the whole of New Zealand (as in 2000, 0–30cm depth), and average amounts per hectare			
Land use	Area (Millions of hectares)	Soil C (Millions of tonnes) Mean and standard error	Soil C content (Tonnes ha <sup>-1</sup> )
Grazing land	14.0	1480±58	105.7
Natural shrub vegetation	2.7	244±18	90.4
Cropland	0.3	26±3	86.7
Exotic forest	1.3	77±23	59.2

*Adapted from: Tate et al (2005)*

The less decomposed material (such as relatively fresh shoot and root material) is generally 'light' and floats, whereas older, more highly degraded material is comparatively 'heavy' often being bound to clay particles. Modern analytical methods using spectrographs and pyrolysis – mass spectrography has revealed a huge range of compounds in addition to the long-chain plant polymers of lignin and cellulose origin. Additional compounds include lipids (fats and waxes), those containing nitrogen (amines and amides) and complexes of these constituents.

To further complicate the identity of soil organic C, most organic matter in soil is intimately mixed with the soil mineral components, particularly clays, iron oxides and aluminum oxides and hydroxides. These form 'organo-mineral complexes' which modify both behavior of the clay and also the organic matter.

### Amounts of organic matter in soils

Soils typically contain around 1–10% organic matter C; New Zealand soils tend to be high in organic C compared to those in Australia and other arid countries. For New Zealand this translates to about 150 tonnes of organic C in the top metre of a hectare of soil. This is a result of high inputs of C from the previous forest vegetation, and the high productivity of our pastures, coupled with a temperate climate and some volcanic ash soils that are particularly good at stabilizing soil organic matter and preventing losses.

The amount of organic matter in soil depends not only on the properties of the soil but also on the type of vegetation at the site (Table 3).

In New Zealand, total C is usually accepted as a good measure of organic matter C, and hence total organic matter. This is because most NZ soils contain negligible amounts of carbonate, which would otherwise add to the total C content. Total C is usually measured in the laboratory by dry combustion or acid oxidation. If required, a factor of 1.7 is usually used to provide an estimate of percentage of soil organic matter (% total C × 1.7 = % soil organic matter).

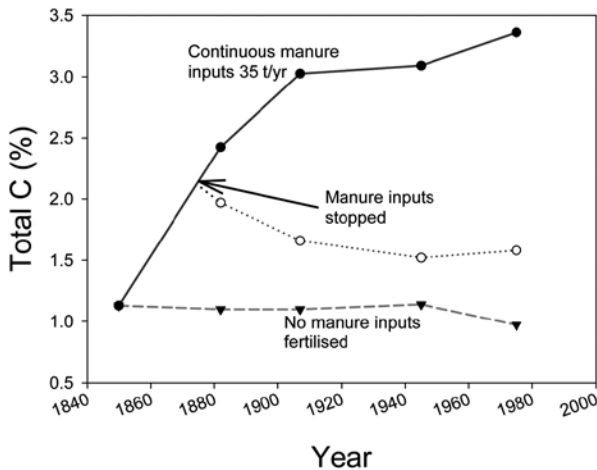
### Cycling of soil organic matter

Most C in soil organic matter has taken many decades to accumulate. However, it does not continue to accumulate forever. Whether there are ongoing losses or gains depends on the balance between the inputs of fresh organic material to soil and losses through decomposition back to CO<sub>2</sub> or losses through topsoil erosion.

Long-term field trials (160 years!) from Rothamsted in England have shown that with regular inputs of organic matter the amount in soil slowly accumulates over many decades or even hundreds of years until an equilibrium is reached (Figure 3). It seems soils have the capacity to store only a defined amount of organic matter.

Why does organic matter take so long to accumulate? When plant residues are added to soil, they start to decompose and after a year only some 30% remains,

with 15–20% remaining after two years, and perhaps 10–15% after three years. The actual amount at any one time is a combination of the nature of the added organic matter, how long it has been there, the soil moisture and temperature. For example grass clippings disappear very quickly whereas bits of wood can remain for many years.



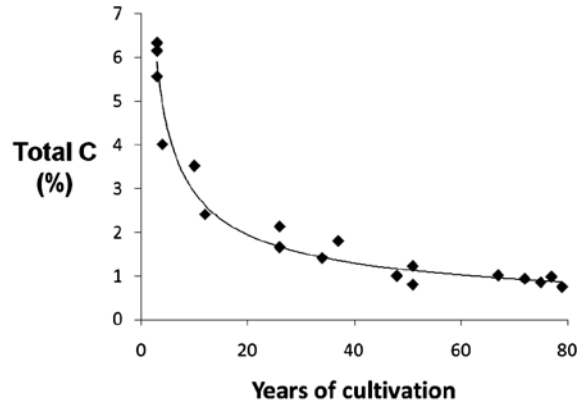
**Figure 3: Organic matter changes at the Rothamsted long-term trials. The dashed line is from a soil used to grow cereal without manure or fertiliser inputs, whereas the solid line is the same soil that has had continuous inputs of organic matter since the 1850s. The dotted line with open circles had added manure until about 1870 when no further inputs were made and soil C then declined. (Adapted from Poulton (1995))**

The amount of organic matter held by soils also depends on the type of soil. Finer textured clay soils usually have more organic matter than coarse textured sandy soils. In New Zealand, mineral soils derived from volcanic ash normally have the greatest amounts of organic matter (8–15% C). The average age of organic matter in mineral soils in New Zealand is about forty to sixty years, but this is only the average, and the organic matter is made up of an old stable fraction that may be hundreds or even thousands of years old; a fraction is five to sixty years old, and the most recent organic matter which may only be one to five years old, or even only months or days (the labile fraction). Some of the older, persistent organic matter in New Zealand pasture soils originally accumulated while the soils were still under the original forest trees.

While organic matter accumulates only slowly in soils, its rate of decline and loss can be rapid. Soils that are regularly cultivated and used for growing crops invariably have much lower soil organic matter contents than the equivalent soils under forest or pasture. Figure 4 shows the change in organic matter C in a Patumahoe clay soil near Pukekohe used for intensive vegetable growing. The soils had accumulated organic matter during a long period under forests. Once cleared and used for arable cropping, the losses of organic matter occurred. Losses were fastest during the first ten years of cultivation, and occur because the decomposition of existing soil organic matter is increased because of tillage and the disruption of soil aggregates, while returns of fresh plant organic material are less because much of the produce is removed from the sites at harvest. Most methods of cultivation and tillage increase the rate of decomposition and loss (decomposition to CO<sub>2</sub> gas) of soil organic matter. Alternative approaches to cultivation and cropping that are less physically disruptive and retain crop residues including minimum tillage or zero tillage (such as direct drill) can help retain soil organic matter.

Even where there is no cultivation, inputs of fresh organic matter to soil are much decreased by the bare ground between row crops or horticulture with little ground cover. Subsequent harvesting leaves the soil bare, and removes a large proportion of the crop off-site. Erosion

processes (both wind and rain) can also relocate topsoil, sometimes many kilometres from its original site. Fire may be useful to clear cereal stubble, but also reduces organic matter returns to soil.



**Figure 4: Losses of soil carbon following the conversion of land to continuous market garden in Pukekohe. (Adapted from Haynes and Tregurtha (1999))**

Peat soils are unusual in having as much as 40–60% total C; hugely more than mineral soils. The extra organic content is because organic matter decomposition is slowed by the acid, wet, anaerobic conditions, and the organic C can persist for thousands of years under natural conditions. These organic peat soils are found throughout New Zealand but the largest areas are found in the Waikato, parts of the Bay of Plenty, the West Coast and Southland.

However, even though the organic matter has persisted for thousands of years as peat, it is susceptible to decomposition particularly when these soils are drained to allow agricultural production. Drainage allows oxygen to enter the soil profile which can accelerate decomposition by micro-organisms. It is not uncommon for the surface of deep peat soils to decline by 1–2cm in just one year depending on land management. Avoiding over-draining these soils by keeping the water-table close to the surface can reduce peat losses.

### Conclusion

Soils store substantial amounts of C in soil organic matter, and the amounts are an important component in the global C cycle. Soil carbon is critical to the maintenance of healthy soils, improving their structure, allowing infiltration of water and air, holding on nutrients important for plant growth and as food and habitat for a wide array of soil organisms. The forms of soil organic matter are complex and decompose at different rates, but are all originally derived from input from plants and animals. Land management practices can alter the amount of C held in soils, often soil C is lost more quickly than it is gained and so careful stewardship of our land is needed.

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