4 Soil organic matter

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4.1 Introduction

It is the presence of organic matter that makes the difference between a collection of mineral particles and a functioning soil with a recognisable physical structure that provides a suitable medium for plant growth. Soils often contain only a small quantity of organic matter (typically a few per cent by mass in agricultural soils), yet this has a major influence on soil properties. For example, organic matter is a key factor determining the interactions between mineral particles and thus the formation of aggregates of varying size and stability and the distribution of spaces (pores) between the solid particles which may be filled with either air or water. This physical structure, relying in large part on the quantity and type of organic matter, determines whether or not a soil retains water, whether it becomes flooded or is well drained, whether it becomes easily compacted or retains a structure conducive to root growth. Organic matter also provides substrate for soil organisms and, often, anchorage points for bacteria or fungi. Interactions between organic matter, organisms and mineral particles form the basis for nutrient transformations on which all plant growth depends. Organic matter is a reservoir of many plant nutrients (such as N, P and S) and also provides a substantial part of the soil's cation exchange capacity (CEC), which is important for the retention of many nutrients. It is also the repository of organic carbon (C) in soil which, on a global scale, is the largest terrestrial stock of carbon after carbonate rocks. Thus, the influence of management practices on the quantity of organic C in soil is vitally important both for the maintenance of soil functions, and its influence on plant growth, and for its impact on global carbon cycling and climate change.

Even a small quantity of organic matter can have a profound influence on soil properties. Soil in arable cropping in a temperate climatic region may typically contain 1–5% organic carbon, yet small variations within this range have a large effect on soil properties.

Soil Conditions and Plant Growth. Edited by Peter J. Gregory and Stephen Nortcliff.
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4.1.1 Terminology – organic matter or organic carbon?

It is customary to refer to the total amount of organic matter (OM) in soil, in all forms, as soil organic matter (SOM). But chemical analysis normally gives a value for C content. It is common to use a conversion factor of 1.724 to convert a measured organic C value to organic matter, implying that organic matter contains 58% C, though this is based on work conducted in the nineteenth century. Values up to 2.0 for surface soils and 2.5 for subsoils have been published (Nelson and Sommers, 1982). A more recent review of data (Pribyl, 2010) shows that the value is variable but an average conversion factor of 2 (i.e. 50% C in organic matter) is more accurate in almost all cases. However, it is now strongly recommended not to quote OM values but use organic C, usually termed soil organic carbon (SOC).

When soil samples are analysed for organic C content, the result is conventionally expressed in units such as %, mg C kg^{-1} soil or μg C g^{-1} soil. These are units of *concentration*, though they are often incorrectly referred to as C *content*. To express C as a quantity or content rather than concentration, the concentration is multiplied by the mass of soil to a given depth, often determined from measurement of bulk density. SOC content can then be expressed in units such as Mg C ha^{-1} or g C m^{-2} to the defined depth. When expressed in such units, the quantity of C in 1 ha of soil can correctly be termed a C content or stock. Alternatively, the value may be multiplied by an area to give a C stock in an area of interest such as Europe, often in units of Tg or Pg. A term sometimes used in such studies is 'C density', which is synonymous with 'C stock per unit area'. Figure 4.1 shows an example of a C density map for the Amazonian region of Brazil (Cerri et al., 2007). In this region there is at least a fivefold range between areas with the lowest and highest C density. From the viewpoint of maintaining SOC stocks (as discussed later in relation to climate change mitigation), such maps can be useful as a tool for policy makers in determining appropriate land management practices for each area. For areas with a large C density, there is a priority to maintain them in their current state in order to avoid C loss and thus prevent the large C stock becoming a source of CO_2. For areas with a small C density, there may be potential to accumulate SOC through altered management or land use, thus creating a sink and helping to mitigate climate change. However, in many cases, a small C density reflects a small potential for SOC accumulation, either because of soil type (e.g. sandy soils which have less capacity to stabilise C than soils with a greater clay content) or through limited plant growth resulting from climatic factors such as low rainfall.

4.1.2 Analysis of SOC

It is now most common to analyse soil for C by high temperature combustion of a sample in the presence of oxygen; various commercial instruments are available for this, using a small finely ground soil sample. All C in the sample is converted to CO_2 and its quantity measured by a gas chromatographic detector, infrared analysis or (less commonly) gravimetrically. If the soil contains carbonate, the C contained in this will also be converted to CO_2, so the quantity derived is *total* soil C. To determine *organic* C, a separate analysis for *carbonate C* is made and this quantity subtracted from the total C value from combustion. Carbonate C is usually determined by treatment of a soil sample with dilute acid and measurement of the volume or mass of CO_2 evolved.

Before the advent of combustion instruments, it was usual to determine organic C by chemical oxidation by heating a soil sample with a mixture of potassium dichromate, sulphuric acid and, in some methods, phosphoric acid. Either the evolved CO_2 was determined gravimetrically or the amount of unused dichromate oxidising agent determined,

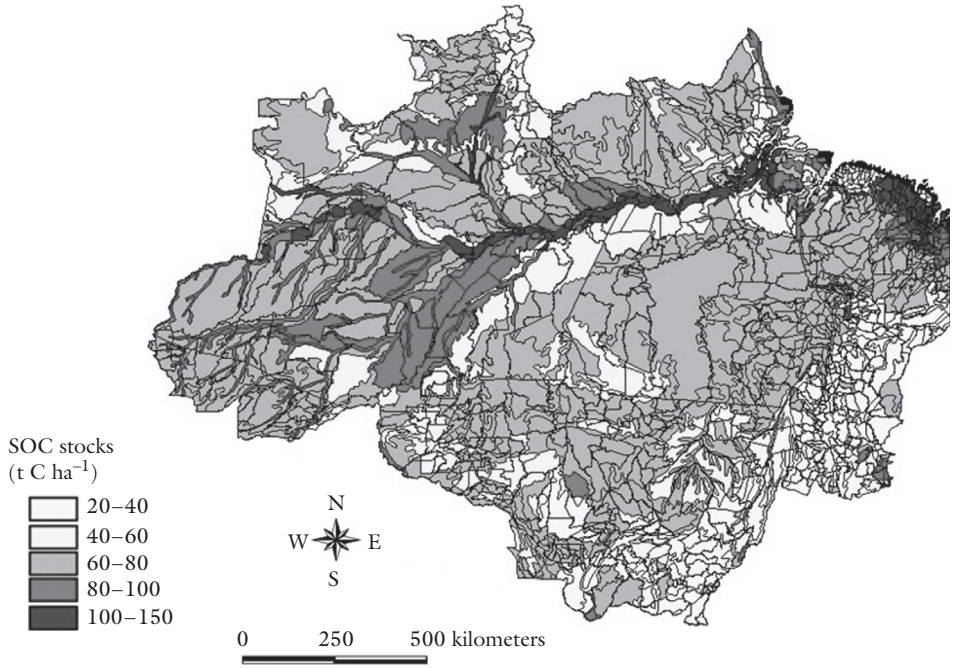

Figure 4.1 Map of soil organic carbon stocks (carbon density) in the Brazilian Amazon. Reprinted from Cerri et al. (2007). With kind permission from Elsevier. For a colour version of this figure, please see Plate 4.1.

often by titration against ferrous ammonium sulphate which was oxidised. Many variations on this principle have been published and used; see Nelson and Sommers (1982) and Kalembasa and Jenkinson (1973) for details of methods and discussion of their merits and limitations. One variation, known as the Walkley–Black method, relies on the heat naturally generated from the reaction between organic matter and the oxidising agent. In well-equipped laboratories, this method would rarely be used now, but in less well-endowed laboratories it is still in use and one sees reference to it in the literature.

An approximate method of analysis, suitable for soils with a high organic C content and where very large numbers of samples require analysis, is *loss on ignition*. In this method a sample is burned and the loss of mass determined. The sample is either dried first (so that water does not contribute to the mass loss) or a correction is made for the small water content of the soil which is normally air-dried prior to analysis. The assumption is that the loss of weight is due entirely to the destruction of organic matter, with the mineral components remaining.

4.2 Factors influencing SOM content

4.2.1 Inputs and outputs of organic carbon

The quantity of organic matter (or organic C) in soil is a balance between inputs and outputs (Figure 4.2). In agricultural soils, the main organic C inputs are plant roots and associated material (sloughed off roots cells, root exudates) and above ground plant parts (stems, fallen leaves, any other non-harvested plant parts) plus any manures or similar materials applied. Minor inputs might include organic matter in dust deposited at a site. The main output of C

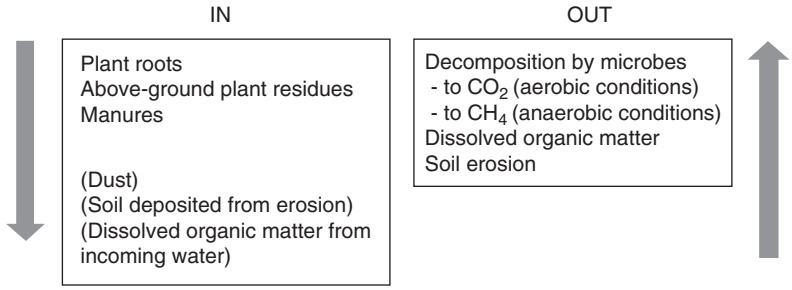

Figure 4.2 Inputs and outputs of C to and from soils.

is decomposition by the soil biological population: under aerobic conditions, C from decomposition is evolved to the atmosphere as CO_2 but under anaerobic conditions, such as in flooded soils growing paddy rice or natural or man-made wetlands, it is methane, CH_4. The rate and extent of decomposition is determined by environmental factors, especially temperature and soil moisture content. Decomposition will almost always be faster at higher temperature than lower assuming sufficient water is available for microbial activity. Very dry or very wet conditions will normally slow decomposition. Because of the generally increased rate of decomposition under warmer conditions, it is usual for soils in tropical regions to have a lower SOC content than those in cooler climates but under comparable land use.

4.2.2 Impact of management practices

Management practices, through their impacts on C inputs and decomposition rates, have a major impact on SOC content but changes often occur slowly – though faster under warmer climates. In this section several examples are presented to illustrate some of the main impacts and trends observed.

Figure 4.3 illustrates several aspects of management impacts on the SOC content of an agricultural soil in a temperate region. The data show SOC content in several treatments of the long-term Broadbalk Experiment at Rothamsted Research, UK, and also a simulation of the data using the RothC model (see Section 4.3). By the year 2005, the SOC content in the treatment given a high rate of farmyard manure (FYM) every year since the start of the experiment in 1843 was almost three times that in treatments given neither manure nor inorganic fertilisers. But the increase occurred slowly and the tendency of SOC to move asymptotically towards a new equilibrium value is clear. The annual rate of SOC increase was much greater in the early years: output from the RothC simulation shows that the average annual increase during the first 20 years was 1.0 t C ha^{-1} but during the last 20 years was only 0.2 t C ha^{-1}. Consequently about half of the final observed increase occurred within the first 30–40 years of manure application. During the period 1926–1966, all plots on Broadbalk were bare-fallowed one year in five, to control weeds, and no manure was applied in the fallow years. Thus, organic C inputs were reduced in these years due to absence of manure and absence of inputs from crop roots and stubble. The small decrease in SOC during the fallow years gives rise to the 'saw-tooth' shape in the simulations. The overall effect during this 40 year period was a small decline in SOC content in all treatments but is most clearly seen in the FYM treatment. After fallowing ceased (because weeds were controlled by herbicides), the increasing trend in the FYM treatment resumed but at a slower rate as the soil tended towards a new equilibrium value. If the soil had not had fallow years during this 40 year period, the new equilibrium value would presumably have been attained earlier and the

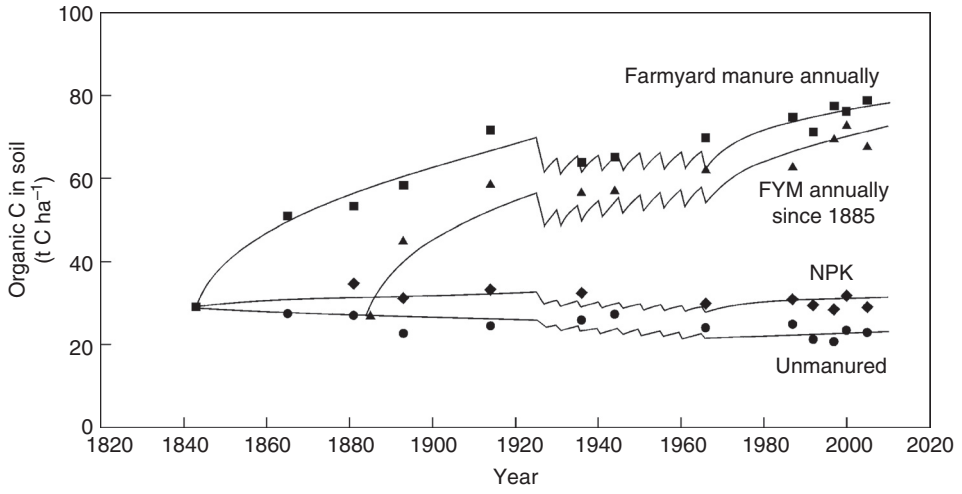

Figure 4.3 Changes in SOC content (0–23 cm) in selected treatments of the Broadbalk Wheat Experiments at Rothamsted Research, UK. Soils analysed using modern combustion methods on either recent samples or those from the archive. Values corrected for changes in soil bulk density. Treatments are farmyard manure (FYM) applied annually either since 1843 (■) or 1885 (▲) or inorganic fertilisers only (including N, P and K at 144, 35 and 90 kg ha^{-1}) annually (◆) and the unfertilised control (●). Points are measured values and lines are simulations using the RothC model. From Powlson et al. (2012). With kind permission from Elsevier.

annual rate of SOC increase in the later years would have been even less. The same trend can be seen in the later FYM treatment that started in 1885.

A surprising result in Figure 4.3 is the fact that SOC in the control treatment with no manure or fertiliser inputs did not decline but remained stable for the duration of the experiment. This is thought to be because the site had been in arable cropping for many centuries; the field is documented as arable at least 200 years before the start of the experiment and is thought to have been initially cleared of natural vegetation at least 1500 years earlier. So the high SOC content under native forest presumably declined during this long period and reached a new low equilibrium value that is maintained by the small crop inputs in the unfertilised and unmanured treatment. In the treatment receiving inorganic fertilisers, crop yields were much higher than in the control (similar to yields in the FYM treatment), so the organic inputs to soil from crop roots and stubble were also greater. This small increase in the annual input of organic C led to a small increase in SOC compared to the control treatment. This is a general trend seen in many long-term studies. Ladha et al. (2011) reviewed data on this point from 135 studies at 114 long-term sites worldwide. On average, application of inorganic N (often with P and K) led to the SOC and soil organic nitrogen (SON) contents of soils being 8% and 12% greater than in the corresponding controls. However, in many cases there was a general decline of SOC and SON over time in all treatments at the sites, and inorganic fertiliser applications did not reverse this; rather the decrease was slightly less where inorganic fertilisers were applied. These observations at so many sites contradict the claim that is sometimes made that inorganic fertilisers, especially N, cause a loss of SOM.

Figure 4.4 (redrawn from Gollany et al., 2011) shows data from a site where natural vegetation was cleared more recently than at Broadbalk, namely, the Morrow Plots in Illinois, USA. This is the oldest agricultural experiment in North America. The native prairie grassland was cleared in 1876 and a range of arable crop rotations and manure or fertiliser treatments established, though the data shown only starts in about 1905. It can be seen that