# CALCULATING THE EFFECT OF ORGANIC MATTER ON SOIL WATER, NUTRIENT AND CARBON STORAGE

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## Abstract

The benefits of increasing soil organic matter include carbon sequestration and an increase in the capacity of the soil to store water and nutrients. However, estimates of the level of potential benefits differ considerably. The calculations are straight forward for carbon but for water storage there can be no definative answer. The calculations are examined and the general levels of benefits identified for different soils.

## Introduction

The benefits of increasing soil organic matter include carbon sequestration and an increase in the capacity of the soil to store water and nutrients. However, estimates of the level of potential benefits can differ considerably. Some of the differences arise because of differences in assumed boundary conditions, as with differences in soil depths and bulk densities, but others are due to the method of calculation. For water in particular some calculations are based on invalid assumptions and provide incorrect results.

The calculations for carbon are straight forward and definitive but for nutrient and water storage there can be no general answer. The result depends on a number of factors that vary considerably between soils. In consequence, the magnitude of change can vary greatly even for apparently well defined conditions.

While there is no definitive answer calculations can be used to identify the general level of expected changes. The calculations are examined below.

## Gravimetric Measurement

Measurements of soil water, and carbon are usually referenced to the dry weight of soil. For water it is typically the weight of stored water as a percentage of the dry weight of soil. The general nutrient storage capacity is given by way of Cation Exchange Capacity (CEC) in milli-equivalents per unit dry weight.

### Carbon

The gravimetric measurement is unambiguous and for carbon there is a single definitive answer. Changes in organic matter directly translate into reasonably well defined changes in the weight of carbon. The relationship between the weight of organic matter and weight of carbon varies with the form of organic matter but it is reasonably consistent with 1gm of carbon equating to around 1.7gm of organic matter.

The quantity of carbon depends proportionally on the depth of soil used in the calculations. As the level of organic matter typically decreases with depth, often rapidly, the gravimetric measurements usually relate to sampling over depth increments of around 10cm. The change in organic matter with depth need not introduce excessive error provided the vertical variation is adequately sampled.

## Water

The gravimetric soil water content is the weight of water in a soil expressed as a percentage of the soil dry weight. The soil water potential identifies how tightly the water is held. Extracting water from soils requires application of a force to counteract the various surface forces that bind water to soil materials. The force required to extract water from the soil is termed the water potential.

The soil matric potential is associated with soil structures and hence with the soil water storage. The osmotic potential is associated with dissolved salts that can move with the water. The total potential is usually given as being the sum of the component potentials.

The relationship between water content and water potential, which represents the water release characteristic of the soil, identifies changes in the availability of the water to plants as soils become dry. Much of the water stored in soils is freely available but the supply becomes increasingly restricted as the soil dries. Notionally no soil water is available to plants below a water potential of -1.5MPa but some plants, such as brigalow, can extract water at potentials below -4.5MPa.

The unit of Pascal identifies that the water potential can be expressed as a pressure. The negative sign identifies the water availability is restricted relative to free water hence a suction is required to extract it from soils. Direct measurement of the negative pressure is only possible for freely available water as the water column snaps at around 0.7 atmospheres in tensiometer instruments. Lower pressures (higher tensions) that exist in drier soils are measured indirectly, generally by measuring the dryness of the atmosphere in equilibrium with the soil.

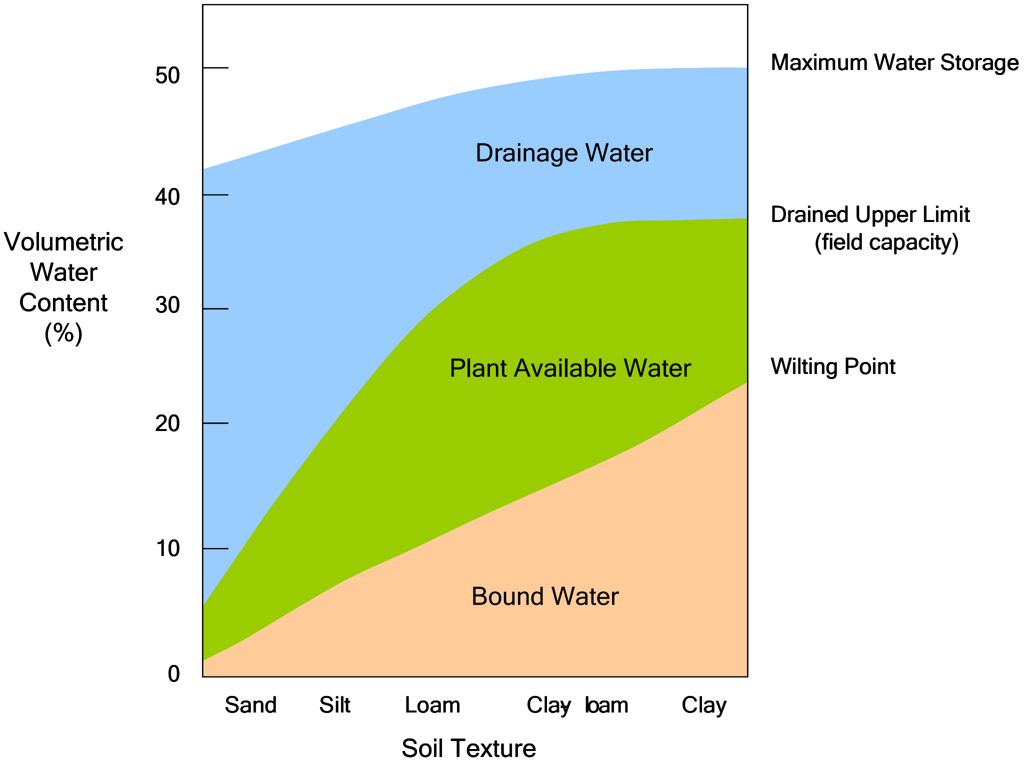

**Fig. 1** Indicative changes in the water holding characteristics of soils with change in soil texture.

In calculating the effect of carbon on soil water it is the water available to plants that is of interest and not the total soil water storage. The available soil water represents the change in soil water storage between soils becoming wet with rainfall and dry through the use of the water by plants. It is generally referred to as the available water holding capacity (AWHC), or available water storage capacity.

The wet threshold is referred to as the field capacity or drained upper limit (DUL) (Fig. 1). It is the maximum water holding capacity of a freely drained soil. The dry threshold has traditionally been referred to as the wilting point as, given prior limitations in the ability to measure water availability, the limit to water extraction from soils was initially thought to be the same for all plants. The nominal wilting point is a water potential of -1.5MPa. Given the steepness of the relationship between water content and water potential at -1.5MPa this assumption of a constant lower threshold for water potential is of no practical consequence in calculating the AWHC.

The bound soil water that is unavailable to plants is mainly associated with clay surfaces. It roughly increases linearly with increase in clay. The drained upper limit depends mainly on the coarse soil structure given by voids. The volume of voids capable of holding water against the force of gravity initially increases with increase in clay content but eventually saturates (Fig. 1). The AWHC tends to be greatest for clay-loam soils.

The water release characteristics of coarse textured soils can often be reasonably predicted from knowledge of the particle size distribution (texture). This arises because most of the water is held in voids and the distribution of void size depends on particle size. The water release characteristics of soils containing a mixture of clay and coarser particles are poorly predicted from their texture because the relationship depends on surface forces within clays as well as voids. Both the surface forces and void structure depend on factors such as clay mineralogy, organic matter, and the level and composition of salts.

The measurement of AWHC is reasonably time consuming and therefore involves an appreciable cost. The DUL should be determined for undisturbed samples as it depends strongly on coarse structure. Technically the -1.5MPa dry limit should be determined using a psychrometer that measures the total soil water potential but it is typically measured using a pressure plate that only controls the matric potential.

Given the difficulties of measurement the AWHC is mostly determined using equations to predict the water release characteristics of the soil from other properties such as texture. These can provide realistic values but predictions can also contain considerable error. In most situations the AWHC of a soil is loosely known. The generalised results in Fig. 1 are indicative only and there is large variation.

## Nature of the soil water reservoir

The storage of plant available water in soils is highly dynamic as soils intermittently wet with rainfall and gradually dry through evaporation. Fig. 2 illustrates the general fate of rainfall. Currently across Australia on average around 20% is evaporated from plant and soil surfaces, 12% flows to streams as surface runoff, and 2% percolates through the soil into groundwater systems. The bulk of the water (~65%) is transpired by plants and that water is extracted by plants from the available soil water storage. The water transpired by plants is identified as being green in the illustrations because it is essential for plant growth.

The pattern of soil water storage is represented by a triangle as the dynamic water storage decreases with depth. This arises because water enters through the soil surface and is extracted from throughout the entire profile by plant roots. The pattern of effective water storage with depth varies depending on the characteristics of the soil, vegetation and climate but a triangle is realistic. This pattern identifies that the surface soil is most important for water storage and that is where organic matter is mainly accumulated.

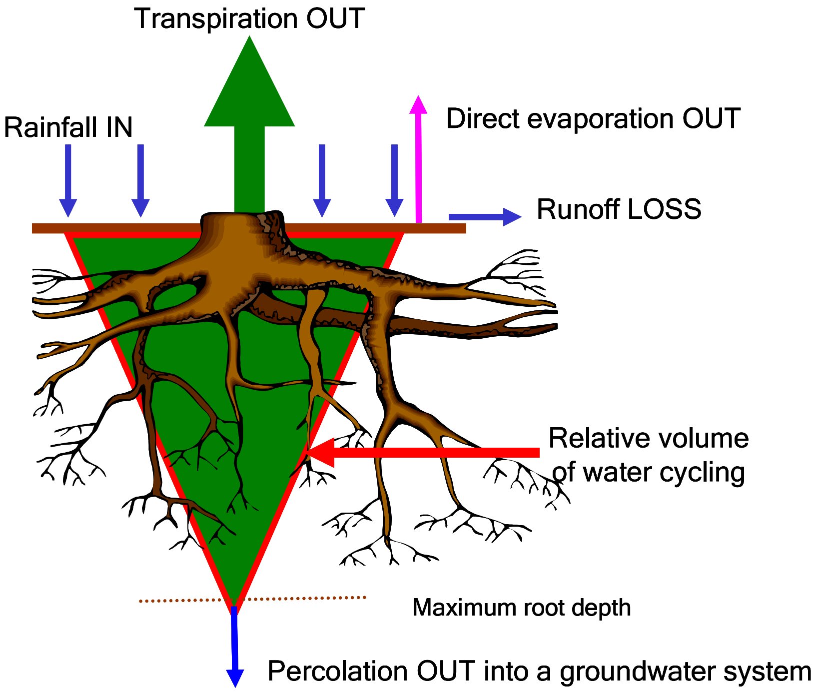

**Fig. 2** Schematic representation of water accessions, losses and storage in soils. The relative volume of water recycling reflects the relative contribution to water storage of soil at different depths.

### Effects of organic matter on soil water storage

The scientific literature is clear that AWHC increases with increase in organic matter. While organic matter increases the amount of bound water it produces a greater increase in the drained upper limit (Fig. 3). However, the results vary considerably depending on the mineral composition of the soil, the form and level of organic matter, and whether the associated changes in bulk density are considered. For levels of organic matter of interest for agriculture the general gravimetric increase in AWHC is around 2.3% for a 1% increase in organic matter, with a range from around 0.8 to 8%. In some situations it can be negative for heavy clay soils.

Similarly to carbon the AWHC depends on the depth of soil used in the calculations. In calculating the AWHC the greatest uncertainty is often the assumed depth over which plants can extract water. The depth used can vary considerably in representing an observed rooting depth, the depth of the soil profile, or the rooting depth expected for the plant type and soil properties.

The AWHC is typically calculated separately for surface and subsoils because of the differences in their properties. However, when addressing changes in organic matter only the surface soil is generally of interest. Subsoils can accumulate appreciable organic matter but typically only with swamps and native grasslands on heavy clay soils.

## Nutrients

The effect of organic matter on nutrient storage can be calculated from the additional storage due to the organic matter assuming that nutrient absorption is determined by the chemical composition of the constituent components with no interactions. However, the ability of organic matter to adsorb nutrients, as given by the CEC, varies greatly compared with the CEC of other soil constituents (Table 1). The difference in CEC between different forms of organic matter is greater than the CEC of the highest mineral soil component hence there can be wide variation in the effect of organic matter depending on its form. The forms of organic matter having greatest effect are colloidal similarly to clays.

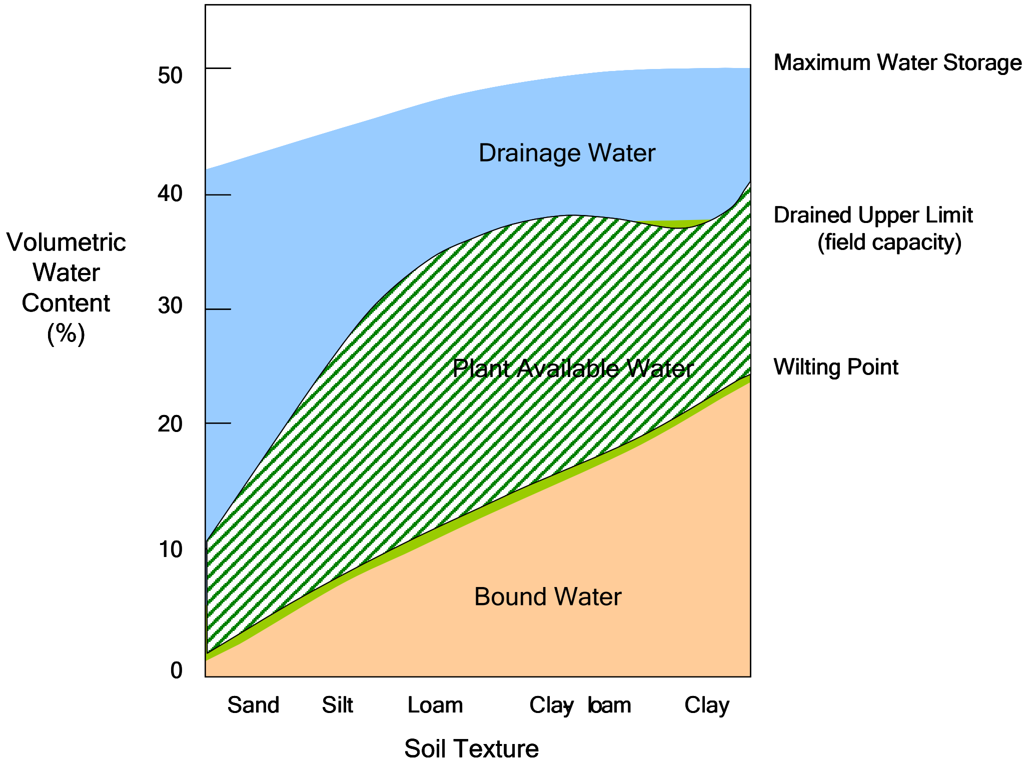

**Fig. 3** Indicative changes to the water holding characteristics of soils with a 2% increase in soil organic matter.

**Table 1.** Characteristic cation exchange capacities of soils and soil components (meq/kg).

| Material | CEC | | Soil Texture | CEC |
|---|---|---|---|---|
| Kaolinite | 30-150 | | Sand | 10-50 |
| Illite | 150-400 | | Fine Sandy Loam | 50-100 |
| Montmorillonite | 800-1000 | | Loam | 50-150 |
| | | | Clay Loam | 150-300 |
| Organic Matter | 2000-4000 | | Clay | >300 |

While the magnitude of the contribution to the CEC by the organic matter may not depend on the soil mineral composition its significance does. Kaolin excepted, the proportional change due to organic matter is greatest with coarse textured soils and decreases as the level of clay increases. The addition of organic matter is most significant with coarse textured soils and poorly structured clays such as Kaolinite. Addition of 2% organic matter to sand produces a 20 fold increase in CEC while the same amount added to a clay soil with 50% montmorillonite will roughly double the CEC. Organic matter is always highly significant for nutrient storage

## Volumetric Measurement

With the gravimetric calculations it is assumed that the density of soil is the same as for water. That is, one liter of soil is assumed to weigh1kg. However, soils are typically denser than water and this higher density must be taken into account to derive absolute changes from gravimetric measurements.

The relationship between soil volume and weight is given by the soil bulk density. A friable surface soil will have a similar bulk density to water in being close to one. The bulk density of subsoils can be higher than 1.6 while rock is often around 2.3.

For all variables the absolute value is given by the gravimetric value multiplied by the bulk density. However, organic matter typically reduces the bulk density and increases the soil depth, and the increase in depth usually more than compensates for the reduction in bulk density. Changes in bulk density and soil depth should be addressed.

One consequence of addressing volumetric change is that there is a finite limit to the amount of water a given depth of soil can store. This produces a limit to the increase in water storage possible with increase in organic matter without there being a change in soil depth. Subsoils are typically compacted and have limited capacity to increase their water storage other than through expanding. This is evident in swelling clays where the uptake of water significantly increases the soil volume and hence depth.

## System Dynamics

In functional soils around 60% of soil carbon is in long lived forms and most of the remainder is rapidly recycled by microbes. Given the slowness of the changes in the long lived fractions of soil carbon the temporal changes can readily be characterised using infrequent sampling. Spatial variations are of most consequence when seeking quantitative estimates.

Soil water shows similar spatial variation to carbon but it additionally changes rapidly with time. Surface soils usually wet and dry many times throughout a year and each time the soil dries the increase in water storage due to organic matter becomes available. With five wetting and drying cycles over a year a 15mm increase in AWHC could potentially produce a 75mm increase in the storage of water that is available to perennial plants.

The additional effects of organic matter in increasing the infiltration rate and decreasing the rate of evaporation from bare soil serve to further increase the water available to plants.

## Calculations

### Carbon

Carbon = Gravimetric OM (%) * Soil Depth * Bulk density / 1.7

The change is expressed in terms of organic matter which is the traditional measurement familiar to land managers. Measurements of total carbon as obtained with an atomic absorption spectrometer include non-organic forms of carbon such as charcoal.

### Nutrients

Change in CEC = Gravimetric Change in OM (%) * CEC of OM * Soil Depth * Bulk Density

Changes due to organic matter determined from this function are based on the assumption that the effect of organic matter is independent of the other soil constituents.

### Water

AWHC = (DUL (%) – WP (%)) * Soil Depth * Bulk density

Organic matter is not a variable in the equation hence it cannot be used to calculate changes in AWHC due to organic matter.

There is currently no reliable predictor for the effect of organic matter on the AWHC. The calculations here are based on results that indicate the increase in gravimetric AWHC is generally around 2.3 times the increase in organic matter. Translating this to a volumetric AWHC requires information on associated changes in soil depth and bulk density.

### Results

Results of calculations are given in Fig. 4 for combinations of changes in soil bulk density and depth. All calculations are for a 2% increase in soil organic matter for a soil with an initial depth of 30cm and bulk density of 1.4.

A 20% decrease in bulk density equates to a 20% increase in soil volume. For the change in soil volume to affect the results the increase in soil depth must be proportionally greater than the decrease in bulk density.

The magnitudes of expected changes for a 2% increase in organic matter over 30 cm for a soil bulk density of 1.2 are illustrated in Table 2. This is the base level for changes expected from improvements to soil health. The percentage increases are very large for nutrient storage but decline rapidly with increase in clay. The increase in water storage is always appreciable and, as with nutrients, decreases with higher proportions of clay.

**Table 2.** Indicative increases in soil carbon, cation exchange capacity and available water holding capacity for a 2% increase in soil organic matter over a depth of 30cm. Rainfall gives the equivalent depth of water.

| **Soil** | | | |
|---|---|---|---|
| **Carbon** | **OM (t/ha)** | **CO2 (t/ha)** | |
| All | 72 | 155 | |
| | | | |
| **CEC** | **(meq/kg)** | **(eg/m$^2$)** | **% Increase** |
| Sand | 600 | 21.6 | ~2000 |
| 'Normal' | 600 | 21.6 | ~400 |
| Reactive clay | 600 | 21.6 | ~100 |
| | | | |
| **Water** | **AWHC (kL/ha)** | **Rainfall (mm)** | **% Increase** |
| Sand | 164 | 16.4 | ~110 |
| 'Normal' | 164 | 16.4 | ~27 |
| Reactive clay | 32 | 3.2 | ~17 |

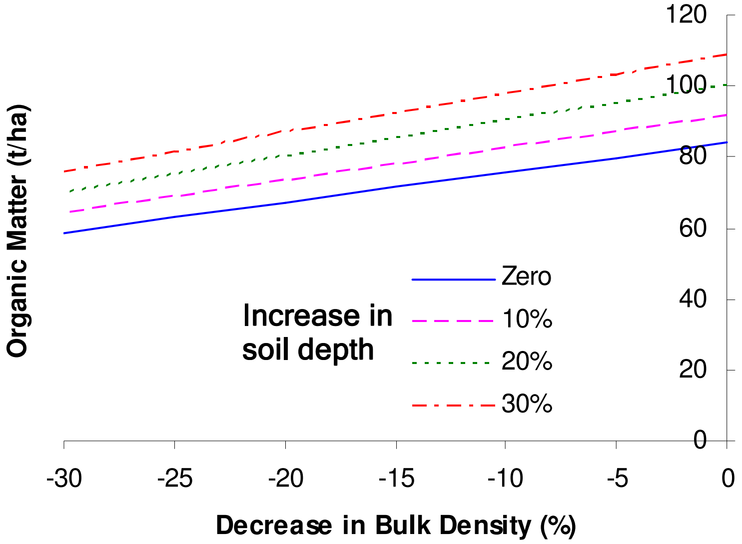

**Fig. 4** Weight of organic matter and water associated with a 2% change in soil organic matter for an initial 30cm depth of soil and 1.4 bulk density for different levels of change in soil bulk density and increase in soil depth.

## Conclusions

The changes in soil carbon sequestration with accumulation of organic matter can be reliably calculated provided changes in soil depth and bulk density are considered, and the field sampling adequately characterises the vertical changes within a profile and the spatial (X,Y) variations in soils. The potential to sequester carbon in agricultural soils is appreciable.

Predictions of the effect of organic matter on soil water and nutrient storage contain large uncertainties because of the number of factors that affect the outcome. The reliability of calculations can be enhanced by incorporating appropriate measurements but the simplest approach is usually to measure the variable of interest rather than rely on predictions.

Despite the uncertainties for particular circumstances the results identify that small increases in organic matter can produce large increases in nutrient storage and appreciable increases in water storage. The percentage increase is much greater for nutrients than water. Also, the percentage increase is much greater for coarse textured soils than clays for both water and nutrients.

The calculations only address storage. Other soil factors important in determining the soil – plant water balance (surficial hydrology) are affected by the levels of soil organic matter, particularly infiltration and hence surface runoff, direct evaporation from the soil surface, and percolation. Also, the significance of the change in soil water storage depends on the efficiency of the water use by plants where this depends on nutrition. Such issues are considered elsewhere in addressing issues such as dryland salinity.