POSSIBILITIES FOR INCREASING AND MEASURING SOIL CARBON

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Abstract

Soil organic matter has always been important for agriculture and is now additionally being assigned value for greenhouse gasses. The value assigned to reducing accessions of greenhouse gasses to the atmosphere provides opportunities to improve the sustainability of agricultural systems by realising on this value to improve soil structure and fertility. Increases in the sequestration of carbon under agriculture are identified as being equivalent to forestry while they have the additional advantage of improving the viability of the existing land use.

Realising on this potential depends on the ability to cost effectively measure increases in carbon sequestration in soils and knowing how to reliably achieve long term gains. Means of monitoring and measuring changes in the amount and forms of soil matter are summarised and some potential developments identified. The need to know the form of carbon currently necessitates laboratory measurements. For practical application these must be combined with spatial mapping of soils to provide area based estimates.

Environmental and management factors affecting the accumulation of soil organic matter are summarised and used to identify conditions best suited to increasing sequestration of carbon in soils. Several management systems that increase soil organic matter are listed. A new initiative designed to aid the implementation of these approaches to management is identified.

Introduction

Carbon is sequestered in the oceans and geologically as well as in organic matter in vegetation and soils. Compared with the approximately 807GT is in the atmosphere, 560GT is in living organisms and 2500GT in soils, with around 1550GT as soil organic matter. While only a small fraction of the carbon sequestered as fossil fuels and carbonates, the amount of carbon in soil organic matter is appreciably greater than in the atmosphere.

Estimates of the amount of soil organic carbon mineralised mainly as CO2 due to human land use over the past 50 years range from 44 to 537GT (Mae-Wan Ho, 2005). This represents an average emission of from 0.9 to 10GT/yr compared with the 7.9GT/yr released by human activities. A potential exists to significantly increase the fixation levels and reduce losses by reversing the current soil degradation (1 to3GT/yr) and reducing net forest clearing (1.6GT/yr).

Terrestrial ecosystems are attractive for carbon sequestration because they can be managed. The focus has been on woody vegetation, essentially trees, because methods exist that can provide reasonable estimates of carbon accrual at commercially viable costs. Soil carbon is now receiving increased attention because of its potential significance but measurement difficulties have limited its value in carbon trading. Protocols allow for soil carbon in agricultural lands to be added to trading schemes but this depends on the availability of cost effective and reliable means of measurement.

The half life of humic compounds in soils is around ten times that of tree carbon and soil carbon can be greater than in live vegetation. As agriculture provides large areas there is a large potential for carbon sequestration. Moreover, increasing carbon sequestration in agricultural lands provides additional benefits such as increased production, reduced need for inputs such as fertiliser, and reduced environmental impacts such as erosion.

A 1% change in organic matter to a depth of 10 cm represents around 5.8 tons/ha of carbon. An average increase of 2% organic matter to a depth of 30 cm, which is readily achievable in many clay soils, represents a sequestration of 35 tons C / ha or 128 tons of CO_2 per hectare with an assumed bulk density of 1. The amounts compare favourably with levels achievable with forestry and can be attained with improvement in the productivity and profitability of the agricultural land use. The total quantities of carbon that can be practically sequestered are likely larger with agriculture than forestry because of the extent of lands that can be profitably allocated to the purpose.

Trading in soil carbon is limited by knowledge of how and where to obtain benefits as well as by measurements. Forestry operations for timber production have been well studied and conditions required for commercial viability are generally well known. Costly mistakes still occur where insufficient attention is paid to the soil and climatic requirements for species but carbon sequestration through trees can be achieved with low risk. By comparison the risk with soil carbon would currently be considered to be high. Reducing the risk depends on the identification of reliable means of achieving as well as measuring increases in soil carbon.

This paper summarises possibilities for estimating soil carbon where remote measurements are desirable because of the spatial coverage and low unit areas costs. However, it also examines the practicalities of increasing soil carbon sequestration in agriculture by way of climate, soils, vegetation and land use. Measurement of soil carbon is of little use without knowing where and how soil carbon sequestration can best be achieved. Organic matter is 1.724 times the amount of organic carbon and CO_2 is 3.664 times the amount of carbon.

Table 1. Forms, longevities and relative levels of ‘soil’ organic matter.

Location	Form	Longevity	Level (% of above ground biomass)
Soil surface	Litter	days-years	1-10
Below Ground	Roots	days-decades	30-50
	Invertebrates	weeks-months	0.01-10
	Microbes	days-weeks	0.01-100
Soil Organic Matter	Carbohydrates +	days-weeks	0.01-30
	Glomalin	years-decades	0.01-100
	Fulvic acids	years-decades	0.01-100
	Humic acids	100-1000 years	0.01-100
	Humins	100->1000 years	0.01-100

Carbohydrates + A wide range of generally short lived organic compounds that includes carbohydrates, fats, waxes, alkanes, peptides, amino acids, proteins, lipids, and organic acids.

Measurement issues

The purpose of the measurement determines what is measured and the required levels of accuracy and spatial detail. Table 1 lists different forms of organic matter often included in assessments of soil organic matter where many are not part of the soil. Moreover, the rapid turnover of many components limits their value for carbon sequestration.

Humic compounds are of most consequence as, due to their longevity, they comprise around 70% of soil organic matter. Use of measurements of humus to quantify carbon accruals represents a low risk. Measurements of cellulose and other more transient compounds can be useful but their inclusion in a budget represents a risk unless their breakdown is reliably accounted for. The conversion efficiency from plant organic matter to humic compounds is around 10%.

The protein glomalin has been identified as comprising around 30% of soil organic matter noting that it not included in many estimates of soil organic matter. Its levels and half life can make it significant for estimates of sequestration.

Soil organic matter has a density around one quarter that of the mineral material hence an increase in organic matter usually reduces the bulk density. This reduction is countered but not exactly balanced by an increase in soil depth hence these changes must be addressed when deriving quantitative estimates using gravimetric observations.

Carbon trading is only viable where sequestration can be reliably estimated at a cost much less than the value assigned to the carbon. Verifiable measurements that take account of vertical as well as horizontal patterns of soil carbon are essential. The methods must be highly efficient.

Measurement approaches

The main division identifies measurements as being direct and indirect. This is subdivided according to the degree of remoteness. Indirect measurements represent variables that respond in some way to organic matter, such as CO_2 emissions.

The degree of remoteness of measurements affects the level of spatial averaging. Destructive field sampling provides point observations necessitating the application of methods for spatial averaging to obtain quantitative estimates. Remote field measurements incorporate spatial averaging, some only in the horizontal plane and others in three dimensions. The reliability of estimates depends on the level of spatial averaging as well as the accuracy of the measurement.

Measurement methods

Optical reflectance (ground, airborne, space)

Optical measurements effectively only provide information for the immediate soil surface. In the laboratory the amount and form of carbon in soils can be reliably estimated from the infrared reflectance spectrum. Separate estimates can be obtained for cellulose, humus and charcoal as well as other soil properties.

The response of organic matter in the infrared potentially provides an opportunity to measure soil carbon with airborne and space sensors and such estimates have been obtained for ploughed paddocks. However, the results are strongly affected by other properties such as wetness and surface roughness. Also, the surface nature of the measurement necessitates empirical correlation with ground observations to produce reliable results.

The considerable research on characterising soil moisture and surface roughness using remote sensing cannot resolve the issues associated with a surface measurement. As the method can only directly provide information on levels of carbon in the immediate soil surface its value lies in providing an effective means of stratifying field sampling. Thermal imagery can also be effectively used for this purpose.

Optical atmospheric absorption (ground, airborne, space)

Optical absorption is typically indirect in measuring the atmospheric concentration of gasses released with the breakdown of organic mater. The measurements therefore characterise some aspect of microbial activity rather than the level of soil carbon. They are useful in addressing land management but not for quantifying the carbon store.

CO2 is the main gas emitted but must be measured in chambers sealed from the atmosphere to obtain an estimate of soil respiration. Other gaseous components deriving from microbial activity can similarly be measured, such as N_2O. Nitrous oxide is released when soil oxygen becomes limiting and microbes utilise nitrite and nitrate. Eddy correlation is used above plant canopies to estimate the total CO_2 flux and can therefore be used to estimate the total carbon being sequestered. The method has traditionally been applied to CO_2 and H_2O but is applicable to any gas that can be rapidly measured at a sufficient level of accuracy.

Emissions of nitrous oxide contribute around 6% CO_2 equivalent of Australia's greenhouse gas emissions and around 80% of the N_2O comes from rural land use. Release from the soil is primarily associated with nitrogen fertilization, soil disturbance and waterlogging. Atmospheric N_2O concentrations measured from space identify that levels become high over rural lands in spring and over crop lands during cropping. The measurement can be obtained at local, regional and global scales. As a flux it is useful for monitoring land use impacts but not for estimating carbon stores.

Radar (ground, airborne, space)

Satellite radar can provide information on surface soil moisture, topography and surface roughness but cannot directly provide information on soil organic matter. Airborne multi-band multi-polarised systems may eventually provide useful information but then likely only for bare soil in flat terrain. Such airborne measurements can currently only be obtained every few years for selected locations in association with research missions.

EM (ground, airborne)

Airborne EM is inapplicable and no current ground system directly provides information on soil organic matter. As the single measurement responds to levels of water and clay and these affect soil carbon it can be used to stratify field sampling but with considerable confounding by other factors such as salinity.

A prototype instrument exists that uses a responsive rather than the current active approach to EM measurement that can discriminate different forms of carbon, such as plastics, cellulose and graphite. The measurements are independent of the usually confounding factors such as iron and water. The discrimination is achieved by, inter alia., the ability to measure up to 12 different variables where the dimensionality allows the separation of different factors similarly to multi-spectral imagery.

The responsive EM measurement can technically provide concurrent measurements of factors of interest, including organic matter, clay and water. Moreover, soil profile information can be obtained by using multiple antennas at a potential vertical resolution better than 10 cm. However, a stand alone instrument suitable for field use has yet to be produced and the first operational instrument will address a very different application.

Any EM instrument must be positioned close to the soil surface and will be affected by surface litter. Application will be best suited to farmed lands noting that the depth discrimination provides a means of removing or reducing the effect of surface litter. Issues of spatial averaging in the x and y directions are the same as with existing EM instruments with surfacing fitting routines being used to interpolate between an irregular grid of observations.

Laboratory analyses

The absolute reference measure is the weight change when soil organic matter is ashed. Another standard procedure involves extraction with NaOH where this does not extract glomalin that comprises around 30% of the organic matter. The results obtained vary with the measurement method. The infra red measurement is quick and provides the most cost effective means of obtaining routine measurements of humic compounds.

Indirect measurements would not be considered for carbon accounting but they provide information beneficial in land management. The cation exchange capacity (CEC) of soils depends strongly on the amount of organic matter but the CEC of organic matter is strongly pH dependent. Measurements of CEC are useful in monitoring the impact of management on soil condition even though they are not applicable for carbon accounting.

Spatial averaging

Measurements of surface fluxes can provide good spatial averages in the x, y and z directions, particularly when obtained from space. With ground measurements such as eddy correlation the horizontal averaging is addressed by providing sufficient fetch but this does not fully resolve the issue if only because the direction of averaging changes with time.

Temporal averaging is an integral part of eddy correlation measurements and the instruments can now provide continuous observations over long periods. However, airborne and space measurements are effectively instantaneous and so must be repeated to monitor changes with time. For airborne observations this can be cost prohibitive. Repeat observations from space are limited by the orbit and spatial coverage of the satellite, and the occurrence of cloud.

Estimates of soil carbon stores currently depend on extrapolations or interpolations of point observations as, unlike fluxes, the measurements of soil carbon levels do not intrinsically provide spatial averages. The distinction between extrapolation and interpolation used here relates to the use of ancillary information to obtain a spatial average. With interpolation the results are based solely on measures of soil carbon. With extrapolation they additionally depend on other factors, such as soil types and land use.

Interpolation

The most common but coarsest approach is to bulk samples from a number of locations either selected randomly or in a pattern thought to sample the variation within a paddock. The latter approach is commonly used but is inappropriate without objective analysis of soil patterns as it effectively prejudges the result.

The approach of analysing one or two bulked samples is difficult to justify as field sampling comprises by far the highest cost and the cost of laboratory measurements has appreciably reduced. Moreover, bulking grossly underestimates the variance and can hide more than it reveals. Bulking is only appropriate where sub-samples are obtained in close proximity in a uniform area that can be assigned a point location.

Averaging by interpolation depends on having observations distributed across the entire area of interest. With field sampling a sampling density of 100m can sometimes be sufficient but a 10m grid may be needed. The appropriate sampling density cannot be determined without field observations of the spatial variability. Interpolation is routinely achieved using surface fitting routines where the data density should be higher than the spatial variability.

Given these constraints interpolation is most common where a grid of point measurements can be rapidly obtained, as with EM and radiometrics (gamma radiation data). It has been successfully applied to laboratory measurements of soil properties such as texture, pH and salinity but at an appreciable unit area cost. The approach is not cost effective where ancillary data are available to allow reliable extrapolation as identified below.

Extrapolation

The traditional survey method involves extrapolating detailed site observations using some form of remotely sensed image. The image provides detailed spatial coverage (mapping) and is related to the attribute being mapped by developing empirical relationships between the image data and detailed observations for point field observations.

The nature of the empirical relationships used can differ considerably. Traditional soil mapping is highly subjective in depending on visual interpretation of aerial photography, topography and anything else considered important. With EM and airborne gamma radiation data (radiometrics) objective numerical analysis can be used to stratify an area into classes wherein the variability within classes is less than between. However, both data types can be analysed as a continuous variable when addressing some factors.

The level of success with such extrapolations mainly depends on the amount of relevant information in the image data. Aerial photography contains little information relevant to soils apart from land use. Existing EM has limited applicability due to the single measurement that responds to a number of soil factors. Radiometrics provide multiple measurements that primarily respond to the nature of parent material and weathering and most of the signal derives from the surface soil. Radiometrics currently provide the most applicable means of stratifying soil sampling and they have the advantage of providing paddock level detail with regional coverage.

Information on land use as well as soils is needed when stratifying sampling to address changes in soil carbon. Optical satellite imagery currently provides the most cost effective and objective means of mapping information such as land use and vegetation type and condition.

Site selection

The ultimate objective is to improve the carbon levels for all soils but the level of potential improvement depends on the climate, soil, vegetation and land management. Site selection is crucial in addressing the profitability of carbon sequestration in soils as verification costs for carbon accounting are comparatively location independent.

The broad controls on the accumulation of soil organic matter are:

- The threshold soil temperature for organic matter accumulation is around 25 C. The soil organic matter roughly doubles for each 10 C decrease in temperature.
- Wet soils tend to accumulate organic matter faster than comparable dry soils.
- Organic matter tends to be higher under grassland than forests.
- Fine textured soils (clays) tend to accumulate organic matter most.

The most suitable sites for accumulating soil organic matter occur in temperate areas receiving good rainfall and have clay soils, as with the main cropping lands in Australia. Areas that receive runoff of rainfall are most suitable.

As grasses preferentially occur on clay soils and waterlogging suppresses most tree species there is a natural synergy between several factors that promote soil carbon accrual. In northern Australia appreciable accumulations of soil carbon only occur on heavy clay soils subject to seasonal inundation that typically support grassland.

The coincidence between the deposition of clay and the receipt of runoff means that suitable sites commonly have depositional soils. However, some mineral materials naturally form clay soils and these can additionally provide extensive areas suitable for soil carbon sequestration.

Land use activities that impact on soil carbon accrual include soil disturbance, irrigation and vegetation and fire management. Fertiliser can increase the rate of breakdown but it can also increase production and the net effect depends on other management practices. Irrigation can increase carbon production and reduce the rate of breakdown but, similarly to fertiliser application, the net effect depends on the management regime. Highest carbon accumulations occur in intermittently flooded rice fields.

Agricultural practices have been developed to increase soil carbon levels due to the associated improvements in productivity. The most general methods are cell grazing and minimum tillage cropping where both reduce the rate of breakdown of organic matter by minimising soil disturbance. Cellular grazing additionally maintains high levels of input of organic matter and reduces soil temperatures. Obtaining good results with minimum tillage involves developing appropriate cropping regimes and cannot be achieved solely by growing cereal crops.

Some management approaches further promote the development of soil carbon by careful management of water in dryland farming. These include Keyline (Yeomans, 2002), Whittington Interceptor Bank technology (Paulin, 2002) and the Natural Sequence Farming.

Potential sequestrations

Several issues arise in the need to maximise inputs of carbon into the soil and to maximise its retention. The soil must promote plant growth and hence develop good fertility and structure. This generally occurs where soils naturally develop levels of organic matter of 2% or more. Moreover, the soil microorganisms must promote retention of the organic matter and not just its breakdown. This situation typically arises where the soil microbial activity changes from being dominated by bacteria to fungi (glomalin is produced by arbuscular fungi).

Laboratory methods exist that address the microbial composition of soils and the potential activity. Field methods can provide measures of total activity. The gap relates to the provision of a rapid method of determining the activity of different microbial components in the field.

Conclusions

An issue for governments in addressing protocols is that carbon balances are referenced to the levels at 1990. The net losses of organic matter from established agricultural lands at 1990 have tangible value. Likewise, increases in soil matter in grazed natural vegetation arising post 1990 through improvements in the management have tangible value. There is value in obtaining retrospective estimates of soil organic matter and hence carbon levels in a wide range of biomes.

Direct measurements of the1990 reference condition are not available for most locations and biomes. Options for indirect determination include assessing the development of different biomes over time with different land uses and relating these to the land use and management history at 1990. Data on the soil carbon levels of representative biomes at different stages of development and condition should enable spatial assessments of changes in the development and health across large areas. The applicability of this approach depends strongly on the ability to map the key characteristics of biomes such as soils, climate and changes in land use and vegetation.

Implementation of this indirect approach for assessing soil carbon levels would require:

- Documenting the natural relationships between the development of different soil-vegetation-climate systems (biomes) and the associated changes in soil carbon

- Documenting the changes to the natural patterns arising from different land management regimes.
- Spatial extrapolation of results using assessments of the patterns of biomes and histories of land use and management.

Healthy Soils Australia (HSA) is developing the above concepts for assessing and verifying soil carbon credits by way of soil measurement and soil, vegetation and land use mapping. The objective is to provide land managers with innovative options for increasing productivity as well as creating and capturing market opportunities for soil carbon credits. The HSA initiative also involves facilitating commercial restoration of shelterwoods and the development of biomass futures strategies. Combined these have the potential to redress a considerable part of Australia's carbon emissions through increasing above and below ground sequestration of atmospheric C. Refinement of the proposed processes for assessing and verifying soil C should promote inclusion of soil C in carbon trading systems and potentially provide a significant demand driver in fostering such improvements.

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