Measuring soil organic carbon stocks – issues and considerations

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Abstract
Increasing soil organic carbon (SOC) stocks has been widely discussed as a short- to mid-term implementable solution to the problem of rising atmospheric greenhouse gas (GHG) concentrations, with the technical mitigation potential of soil carbon sequestration around 5 $GtCO_2eq/yr$ by 2030. However, as the spatial variability of SOC is high, coefficients of variation in SOC stocks can rise sevenfold when scaling up from point sample to landscape scales, resulting in high uncertainties in calculations of SOC stocks. This hinders the ability to accurately measure changes in stocks at scales relevant to emissions trading schemes (ETSs). Further, the depth distribution of SOC has not been thoroughly investigated, resulting in possible underestimations of carbon sequestration due to inadequate sampling depth. Research is needed to eliminate these uncertainties in SOC stocks and enable soil organic carbon to be incorporated into ETSs. Reliable and low-cost methodologies for measuring SOC are also required, so analysis costs do not outweigh carbon credits. When assessing SOC stocks, sampling and analysis must be carefully planned to avoid bias and ensure accurate calculations.

Key Words
Soil organic carbon, sampling, spatial variability, vertical distribution, analysis.

Introduction
In 2005, approximately 10 – 12% of anthropogenic GHGs originated from agricultural activities, mainly as methane and nitrous oxide emissions from livestock and rice farming, with the net flux of carbon dioxide from soils estimated at only 0.04 Gt/year (Smith *et al.* 2007). However, soils store approximately 2344 Pg (1 Pg = 10^{15} g = 1Mt) of organic carbon worldwide - over three times the atmospheric carbon content - (Jobbagy and Jackson 2000) and manipulation of SOC stocks through land-use and management changes has been widely discussed as part of a solution to rising atmospheric levels of CO_2 (Lal 1997; Lorenz *et al.* 2007). The 2007 IPCC report estimated that around 5 $GtCO_2$-eq/yr could be sequestered in soils by 2030 (Smith *et al.* 2007). In order to provide governments and other interest groups with the foundations for effective policy making with regard to ETSs, soil scientists are faced with the challenge of identifying and quantifying the fluxes of soil GHGs. In particular, reliable methodologies and protocols for monitoring SOC stocks must be developed, which ideally are easily implementable and not costly. Baseline measurements of natural systems and current stocks must be made to ensure quantification of anthropogenic induced changes and avoid bias in ETSs. Further, the influence of different management practices and land-uses on SOC dynamics must be understood, as well as the effects of other variables, such as soil type, soil texture, climate, topography and vegetation. Finally, understanding SOC dynamics requires defining appropriate time-scales for monitoring changes and also definitions of efficacy and permanence of sequestration.

Sampling issues
Due to the heterogeneity of SOC distribution, the number of samples required to accurately assess SOC stocks at scales suitable for carbon trading is high. Scaling up of SOC stocks from point sample to landscape unit is problematic and caution should be made that any calculations are based on reliable data. Goidts *et al.* (2009) found coefficients of variation increased from 5 % to up to 35 % in SOC stocks when scaling up from sample to landscape scales in Belgian soils. In his review of global soil carbon storage, Schlesinger (1977) noted coefficients of variation of up to 87 %. Altering management practices in strongly degraded soils to increase carbon stocks by 0.01% per year has been proposed (Lal 1997), but such changes would be undetectable due to the heterogeneity of SOC distribution and limitations of analysis techniques. For carbon accounting purposes, a minimum detectable difference must be defined (mean ± one standard deviation, coefficient of variation within a land-unit?), and SOC changes must lie above it. This requires high resolution data to predict SOC stocks at appropriate scales within the required accuracy so only significant changes are accounted for. In turn, the appropriate scales require definition: which land-units should we investigate - field, farm, catchment? When designing sampling campaigns, taking into account the factors

influencing SOC distribution, such as soil type, land-use, climate, and vegetation will help to optimise sampling depths and numbers, ensuring that samples accurately reflect the distribution of SOC at the site.

In addition to the problems arising from insufficient sample numbers, inadequate sampling procedures can produce a bias in data, leading to incorrect estimations of SOC stocks (Harrison *et al.* 2003). For instance, sampling with cores can lead to underestimation of the coarse soil fractions (> 2mm) due to the inability of corers to sample larger rocks. Gaudinski *et al.* (2000) found that CO_2 flux calculations are very sensitive to estimations of rock content. As SOC content is determined on sieved samples (< 2 mm), disregarding rock content in rocky soils will lead to overestimation of SOC stocks. For example, if rocks account for 30% of the volume of a sample but SOC concentrations and bulk density are determined on sieved samples, then calculating stocks without accounting for rock volume will lead to an overestimation of SOC stocks by 3/7, or over 40%. In soils with low rock content this effect may be negligible, but in soils with high (variability of) rock content, comparability between sampling events will be limited.

Temporal issues
SOC content varies not only spatially but also temporally. For example, comparing samples taken in July one year with samples in January 5 years later is unlikely to provide accurate information on SOC dynamics. So that carbon credits can be generated and traded in ETSs, a definition of and time-scale for assessing permanency of changes in SOC stocks is required. For instance, is permanency reaching steady-state conditions under new management practices? How long do SOC stocks have to remain constant for steady-state conditions to be declared? When are carbon credits generated – after reaching steady state or after a defined increase in carbon stocks? Chan and Hulugalle (1999) detected significant differences in SOC content three years after conversion of agricultural practices, indicating that assessment every few years may be necessary to evaluate SOC dynamics. However, Gaudinski *et al.* (2000) found continuing carbon sequestration over 100 years after reforestation of abandoned agricultural land, indicating that permanency may only be identifiable in the long-term which will complicate ETSs with credit trading on daily markets.

Measuring soil organic carbon
Accurate measurement of SOC content is costly and time-consuming. Determining SOC via wet oxidation and titration (Walkley and Black 1934) produces toxic dichromate waste, and incomplete oxidation can lead to underestimation of carbon stocks. Elemental analysis is assumed to deliver the most accurate results but equipment is costly, representativity is questionable due to the minute amount of sample used in the analysis, and any inorganic carbon present must be separately measured. Loss-on-ignition is low-cost and its reduced accuracy may be the trade-off for lowering of analysis costs and the ability to process more and larger samples, increasing representativity and satisfying the need for high resolution of SOC data.

Recently, infrared spectroscopy (IRS) has been applied to measure numerous soil properties including OC content and composition in bulk soils and soil fractions (Ellerbrock *et al.* 1999; Janik *et al.* 2007; Viscarra Rossel *et al.* 2006). IRS has the advantage of being fast, inexpensive, non-destructive, and requiring little to no sample pre-treatment. However, calibrations with traditional methods are required and accuracy is often limited to local data sets. IR analysis has also been successfully used to measure SOC *in situ*, which appears promising as a reliable, low-cost method for assessing SOC stocks on the field scale (Stevens *et al.* 2008), thus helping to resolve the problem of inadequate data resolution. Before this technique finds widespread application, issues with sampling methodology must be resolved. These include: accessibility to the soil, which must be free from vegetation for reliable measurements; depth of sampling; measurement of bulk density concurrent with SOC concentration *in situ*; and calibration of data sets.

Vertical distribution of SOC and sample depths
The vertical distribution of SOC is controlled by various factors. In reviewing over 2700 soil profiles worldwide, Jobaggy and Jackson (2000) concluded that vegetation and climate were associated with the relative vertical distribution of SOC, but climate and clay content were more important in determining the absolute amount of SOC stored. In surface layers, climate is the dominant control on SOC content, which is negatively correlated with temperature and positively correlated with rainfall. With increasing depth, clay content becomes the dominant control. Therefore, in sandy soils in arid zones sampling to half a metre may prove sufficient, as SOC concentrations in deeper layers may be below the detection limit, whereas in clay rich soils under high rainfall sampling to bedrock may be necessary to accurately assess SOC stocks. Furthermore, pedogenesis can lead to translocation of organic matter (e.g. during podzolisation), so soil type

must also be considered when deciding upon appropriate sampling depths. In summary, different sampling depths may be required dependant upon climate, soil texture and soil type, which in turn creates issues when comparing land-use effects in soils with different physico-chemical identities.

Despite the fact that around 70 % of SOC is located below 30 cm (Batjes 1996), studies of SOC usually investigate topsoils (e.g. Dick 1983; Skjemstad *et al.* 2008). Jobaggy and Jackson (2000) were unable to directly calculate SOC stored below 1 m due to a scarcity of data, instead extrapolating from model distributions computed with data in upper layers. The rationale for investigating the topsoils seems to be that these are the active soil layers with the highest turnover and any changes in SOC stocks will occur here. For example, tilling of soils leads to SOC depletion associated with decreased aggregate stability (Chan *et al.* 2002) and a loss of CO_2 (Reicosky *et al.* 2005). Ease of, and the time and costs associated with, sampling deeper soil layers may also play a role in determining sampling-depth in many studies. However, ignoring deeper stored carbon seems risky when changing stocks could mean taxes or income to land-users. Chan and Hulugalle (1999) reported increases in SOC content 60 cm below the surface of irrigated Vertisols after conversion from conventional to minimum tillage, showing that deeply stored carbon can be dynamic. Defining appropriate sampling depths is essential for accounting purposes and it has been proposed that a depth of at least 1 m is required to assess SOC stocks (e.g. Young *et al.* 2005); Lorenz and Lal (2005) suggest that even this may be insufficient to accurately assess stocks. In any case, many more data are required before we can confidently measure changes in SOC stocks. Initial studies in an area should aim to characterise SOC distribution to bedrock with consequent sampling depths based upon previous data.

Current research needs

Soils are four-dimensional systems, changing across landscapes, with depth and through time. For ETS purposes, high-resolution, low-cost SOC data are required. In particular investigations of SOC variability and distribution at different scales, depths and through time, as influenced by internal and external factors such as soil texture, land-use and climate, are required, allowing confident assessment of SOC stocks and hence generation of carbon credits. Methodologies allowing rapid, easy and low-cost measurements of SOC stocks, such as *in situ* IR-measurements, must be developed so that measurement costs do not outweigh carbon credit payments.

Our research is currently focussed upon investigating the relationship between soil fine mineral content, the vertical distribution of SOC and SOC turnover in Wombeyan Caves, NSW. The karst bedrock above the cave system enables rapid transmission of water to the underground system, providing the possibility of linking SOC activity with dripwater chemistry. Speleothems are well-known environmental and climate archives, and this investigation will enable an initial analysis of the relationship between SOM turnover and speleothem C signals, linking past soil and climate processes.

Conclusions

For soil carbon sequestration to be incorporated into ETSs, SOC stocks and their dynamics must be reliably measured and closely monitored. Currently, insufficient data are available to confidently account for changing stocks, in particular heterogeneity of distribution in landscapes and deeply stored SOC. Closer attention must be paid to sampling procedures and calculations of stocks, with particular regard to the number of samples required to significantly assess stocks at scales required for accounting purposes, vertical distribution of SOC and the rock content of soils. Lastly, time-scales for assessing SOC dynamics and defining permanency are required, so carbon trading credits can be generated.

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