16 Measuring and Monitoring Soil Carbon

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Abstract

Soils are the largest terrestrial reservoir of organic carbon, yet great uncertainty remains in estimates of soil organic carbon (SOC) at global, continental, regional and local scales. Compared with biomass carbon, changes in SOC associated with changes in land use and management, or climate change, must be monitored over longer periods. The changes are small relative to the very large stocks present in the soil, as is their inherent variability. This requires sensitive measurement techniques and due consideration for the minimum detectable difference (MDD). Relationships between environmental and management factors and SOC dynamics can be established using experimental field trials, chronosequence studies and monitoring networks. Soil monitoring networks (SMNs), for example, can provide information on direct changes of SOC stocks through repeated measurements at a given site, as well as data to parameterize and test biophysical models at plot scale. Further, they can provide a set of point observations that represent the (mapped) variation in climate/soil/land use and management at national scale, allowing for upscaling. SMNs must be designed to detect changes in soil properties over relevant spatial and temporal scales, with adequate precision and statistical power. Most SMNs, however, are in the planning or early stages of implementation; few networks are located in developing countries, where most deforestation and land-use change is occurring. Within these monitoring networks, sites may be organized according to different sampling schemes, for example regular grid, stratified approach or randomized; different statistical methods should be associated with each of these sampling designs. Overall, there is a need for globally consistent protocols and tools to measure, monitor and model SOC and greenhouse gas emission changes to allow funding agencies and other organizations to assess uniformly the possible effects of the impacts of land-use interventions, and the associated uncertainties, across the range of world climate, soils and land uses.

Introduction

Soils are needed for the production of food, fibre and timber, and they provide many ecosystem services, largely through the beneficiary functions of soil organic matter (Victoria *et al.*, 2012). Although soils are the largest terrestrial reservoir of organic carbon, great uncertainty remains in the estimates of soil organic carbon (SOC) stocks and their changes at global, continental, regional and local scales (Kogel-Knabner *et al.*, 2005; Milne *et al.*, 2010; Paustian, 2012; Smith *et al.*, 2012). Hence the need for

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a better understanding and quantification of the role of soils and the vegetation they support as natural regulators of greenhouse gas (GHG) emissions and climate change. Documenting such changes requires methodologies for monitoring, reporting and verification (MRV) of C stocks and GHG emissions that follow the principles of the United Nations Framework Convention on Climate Change (UNFCCC): transparency, consistency, comparability, completeness and accuracy (Bottcher *et al*., 2009). The relative importance of accurate measurement of the different carbon pools will vary across land-cover types (IPCC, 2006; Ravindranath and Ostwald, 2008; GOFC-GOLD, 2009; de Brogniez *et al*., 2011). In this respect, the IPCC National Accounting Guidelines recommend prioritizing the measurement and monitoring of the most significant carbon pools and those with the greatest potential to change (IPCC, 2006).

Soil properties vary in space, with depth and over time, with different measurement errors attached to them (Burrough, 1993). Soil monitoring involves the systematic measurement of soil properties to record their spatial and temporal changes. The assessment of SOC stock (changes), at a given site or for a given region, will require analyses of OC concentration, bulk density, content of coarse fragments (>2 mm) and soil depth. To be most effective, however, monitoring activities should consider a larger set of soil variables (e.g. Morvan *et al*., 2007), as well as information on the main biophysical (climate, terrain, soils and land use/vegetation or ‘activity’ data) and socio-economic drivers of change (e.g. Lambin, 1997; Ravindranath and Ostwald, 2008; de Brogniez *et al*., 2011). These variables may be recorded within the framework of a larger soil monitoring network (SMN) or a specific land use and management project. They are also needed for modelling possible changes in SOC stocks and GHG emissions using a range of empirical and process-based tools (see Chapter 17, this volume).

Several steps are needed in any measurement protocol to produce credible and transparent estimates of net changes in carbon stocks. These include: (i) designing a monitoring plan, including delineation/mapping of (project) boundaries, stratification of the project area, determining the type and number of sample plots, selection of C pools to be considered and appropriate procedures for their measurement, and frequency of monitoring; (ii) sampling procedures for field data collection for estimating above- and belowground carbon stocks (mainly, above- and belowground tree biomass; dead wood in standing and downed trees; non-tree vegetation; litter and duff; and SOC). In addition to this, consistent procedures are needed to analyse the results; for soil properties, these should include a quality assurance and quality control plan (IPCC, 2006; Ravindranath and Ostwald, 2008; de Brogniez *et al*., 2011). The focus of this chapter is on monitoring soil carbon changes.

Key issues on SOC monitoring and sampling/analysis approaches are discussed in this paper, based on a review of the recent literature. Drawing from this, main methodological requirements and general recommendations are proposed for ‘good soil monitoring practice’.

Soil Monitoring Networks

Purpose

The primary reasons for collecting most forms of natural resources data are to reduce risks in decision making and to improve the understanding of biophysical processes (McKenzie *et al*., 2002; Ravindranath and Ostwald, 2008; de Brogniez *et al*., 2011). Soil monitoring may be defined as the systematic measurement of soil properties with a view to recording their temporal and spatial variations. SMNs generally comprise a set of sites/areas where changes in soil characteristics are documented through periodic assessment of an extended set of properties (Morvan *et al*., 2008; Arrouays *et al*., 2012). To be most effective, SMNs have to be integrated with other activities that generate essential knowledge for natural resource management, including land resource surveys, environmental/land-use history, field experiments and simulation modelling (Morvan *et al*., 2008; Ravindranath and Ostwald, 2008; Desaules *et al*., 2010).

The complementary benefits of mapping, monitoring and modelling are summarized in Table 16.1 (McKenzie *et al*., 2002). Mapping, for example, is needed to stratify landscapes according to climate, soil type and land use to forecast possible GHG changes for the main source and sink categories (i.e. forest land, cropland, grassland, wetlands and other lands), as considered in the IPCC guidelines (IPCC, 2006; Milne *et al*., 2012).

Methodological considerations

General

There are three main approaches (experimental field trials, chronosequence studies and monitoring networks) to determine the relationships between environmental and management factors and SOC dynamics (van Wesemael *et al*., 2011). A wide range of studies have been published on statistical and other methods of environmental monitoring indicating that it is often cumbersome for a practitioner to extract the relevant information from these diverse materials. For example, the sampling area (block support), number and kind of (sub)samples, depth of sampling, range of parameters to be measured and analytical methods for their measurement often differ from one SMN to another (e.g. Morvan *et al*., 2007; GOFC-GOLD, 2009; Batjes, 2011b; Lark, 2012). The objective of the SMN and its complexity will largely determine which statistical methodology should be used, as there are trade-offs between the different classes of design. A detailed discussion of the different statistical approaches needed to analyse random, grid-based or stratified monitoring schemes, however, is beyond the scope of this chapter (see, for example, De Gruijter *et al*., 2006; Allen *et al*., 2010).

Temporal and spatial scales versus detection limits

Some soil properties can be monitored easily; this includes those properties that vary least spatially, are responsive to management intervention and are the easiest to measure. Compared with biomass carbon, changes in SOC associated with changes in land use and management or climate change must be monitored over longer periods. The changes in SOC are small relative to the very large stocks present in the soil, as well as the inherent variability, which requires sensitive measurement techniques and due consideration for the minimum detectable

Table 16.1. Complementary benefits of mapping, monitoring and modelling. (From McKenzie *et al*., 2002, with permission from CSIRO.)

Complementary relationship	Benefits
Mapping → Monitoring	• Spatial framework for selecting representative sites • System for spatial extrapolation of monitoring results • Broad assessment of resource condition
Monitoring → Mapping	• Quantifies and defines important resource variables for mapping • Provides temporal dimension to land suitability assessment (including risk assessments for recommended land management practices)
Modelling → Monitoring	• Determines whether trends in specific land attributes can be detected successfully with monitoring • Identifies key components of system behaviour that can be measured in a monitoring programme
Monitoring → Modelling	• Provides validation of model results • Provides input data for modelling
Modelling → Mapping	• Allows spatial and temporal prediction of landscape processes
Mapping → Modelling	• Provides input data for modelling • Provides spatial association of input variables

difference. Further, monitoring protocols must be designed to detect changes in soil properties over relevant spatial and temporal scales, with adequate precision and statistical power. For example, the effect of climate change on SOC is observed more readily at a broad scale than at a smaller spatial scale (Wang *et al*., 2010). Alternatively, the precision required for reporting possible avoided emissions, expressed as metric tonnes CO_2-equivalent, will be different (i.e. higher) for a strict 'compliance' (e.g. Kyoto type) than for a 'voluntary' (e.g. Chicago Carbon Exchange (CCX)) project on the carbon-offset market (Kollmuss *et al*., 2008). For the latter, C sequestration is generally seen as an additional benefit next to improving food security, resilience, biodiversity and human well-being/livelihood (Milne *et al*., 2010).

Sampling design and statistical methods

The main difficulty in assessing changes in SOC level at the field, landscape and regional scale is not linked to the accuracy of SOC analysis in the laboratory but to the design of an efficient sampling system (De Gruijter *et al*., 2006; Conant *et al*., 2010). Garten and Wullschleger (1999) were among the first to introduce the concept of minimum detectable difference (MDD). This concept is based on the Central Limit Theorem and provides the smallest difference between two sampling campaigns that can be detected, taking into account the number of samples and the variance of the SOC. According to Spencer *et al*. (2011), a national SMN should enable detection of broad-scale changes in SOC related to multiple drivers such as land use, management and climate change. Such an SMN should contribute to the understanding of the regional C cycle by detecting changes in soil fertility and fluxes of CO_2 between the soil and the atmosphere. Saby *et al*. (2008) applied the MDD concept to evaluate the statistical power of SMNs to detect a certain change in SOC stock. The parameters of the European SMNs such as sampling design, the coordinates of the monitoring sites and the number of sampling campaigns were obtained from questionnaires completed within the framework of the Environmental Assessment of Soil for Monitoring (ENVASO) project (Morvan *et al*., 2007), while the variance of the SOC within European countries was estimated based on the SOC map of Jones *et al*. (2005). Overall, the variance of SOC concentrations increases from Mediterranean countries to colder and more humid north European countries where extensive areas of organic soils occur. As the density of the monitoring sites varies widely between European countries, the MDD is generally high, ranging from 10 to 30 g C kg^{-1} in Nordic countries (Estonia, Luxembourg, Latvia, Northern Ireland and Finland) to less than 5 g C kg^{-1} in southern countries or countries with a dense SMN (England and Wales, Bulgaria, Italy, Greece, Hungary, Romania, France, Portugal, Spain, Belgium, Austria and Malta) (Saby *et al*., 2008). Given an expected mean rate of SOC change of 0.6% C $year^{-1}$ (Bellamy *et al*., 2005), the relatively dense SMNs in most countries will detect such a change in close to 10 years. Similarly, Schrumpf *et al*. (2011) recommend continuous soil monitoring for SOC at time intervals of 10 years as a compromise between detectability of changes and temporal shifts in trends. It should be noted here, however, that this is longer than the duration of many land use and management projects that involve the measurement of SOC stock changes (i.e. for the baseline and at the end of the project). Alternatively, some countries use an interval of 5 years (see Table 16.2).

Spencer *et al*. (2011) evaluated the potential of an SMN on US agricultural lands to detect changes in SOC. They combined model-based changes in SOC, as produced by the Century model for the UNFCCC reporting, with the variance of the estimates of the model runs at a subset of the 186,000 National Resources Inventory sites (NRI). The results of these model runs indicate that the slope of the standard error against the sample size declines after model runs at 6000 NRI sites. They argue that an a priori knowledge of the variance per strata allows an optimal allocation of sampling units, resulting in an efficient use of resources for establishing an SMN.

Table 16.2. Summary of soil monitoring networks and sample design. (From van Wesemael *et al*., 2011.)

	Belgium	Germany	Mexico	New Zealand	Sweden	USA	Australia	Brazil	Canada	China
Objective	National SOC monitoring	National SOC monitoring	National SOC monitoring	National SOC monitoring	National SOC monitoring	National SOC monitoring	Baseline SOC for land use/soil combinations	SOC response to land use/ management change	SOC response to land use/ management change	Regional SOC monitoring
Region covered	Cropland and grassland in southern Belgium	Cropland and grazing land	Forest and non-forest land in particular pasture and shrubs	All regions and land uses	Cropland ~3 Mha	Cropland and grazing land in the USA	Cropland and grazing land[b]	Rodônia and Mato Grosso	No-till sites in Saskatchewan province	North-east (120 sites), north (241), east (356), south (119), north-west (148), south-west (97)
Starting date	National Soil Survey 1950–1970; resampled 2004–2007	November 2010	Started in 2003; each year 1/5 of the sites will be resampled	National soils database from 1938. Land use and carbon analysis system (LUCAS) started in 1996[a]	Full scale in 1995, some data from 1988	Planned	July 2009	2007	1997	78% started before 1985 and 87.5% continued until at least 1996
Site density (km^2 per site)	18 km^2	64 km^2	78 km^2	202 km^2	10 km^2	Croplands: 438 km^2; grazing lands: 1040 km^2	Total number of locations is not known at this time.	N/A	N/A	N/A
Site selection	Stratified	Grid	Grid	Stratified	Grid	Stratified	Stratified	Stratified	Stratified	Stratified

Soil sampling										
Sub-samples	Composite	Composite	Composite	Single	Composite	Composite	Composite	Composite	Composite	Composite
Depth	0–30 cm and 0–100 cm	10 cm slices until 100 cm	0–30 cm and 30–60 cm	Variable, sampled by soil horizon; in 2009, 1235 samples to 30 cm	0–20 cm; 40–60 cm	10 cm slices until 75 cm	0–10, 10–20 and 20–30 cm	0–10; 10–20; 20–30; 30–40 cm;	0–10; 10–20; 20–30; 30–40 cm;	0–20 cm
Frequency	Once, but can be resampled in future if funding is available	Every 10 years	Every 5 years	Resampling is ongoing	1995 and 2005 done, will be repeated every 10 years	Each point will be sampled every 5–10 years	Once, but can be resampled in future if funding is available	Once	Sampled in 1997, 1999, 2005 and 2010	Annual sampling from 2010

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[a] LUCAS network: http://www.mfe.govt.nz/issues/climate/lucas/.

[b] For consistency across the programme the Australian Land Use and Management (ALUM) Classification is used (http://www.daff.gov.au/abares/aclump/pages/land-use/alum-classification-version-7-may-2010/default.aspx).

Following up from the review of European SMNs (Morvan *et al.*, 2007), the Joint Research Centre of the European Commission has launched an initiative to sample the topsoil at 22,000 points of the Land Use/Cover Area Survey (LUCAS project, see Montanarella *et al.*, 2011). LUCAS is based on the visual assessment of land-use and land-cover parameters that are deemed relevant for agricultural policy. The soil sampling at the LUCAS points carried out in 2009 will produce the first coherent pan-European physical and chemical topsoil database. This topsoil survey resulted in a consistent spatial database of the soil cover across Europe, based on standard sampling and analytical procedures. A stratified sampling design was implemented to produce representative soil samples for major landforms and types of land cover of the participating countries.

Further initiatives for national SMNs were retrieved from a questionnaire that was sent to participants of a special session at the SOM 2009 conference in Colorado Springs, USA (Table 16.2). Some SMNs are designed to estimate country-specific land-use or management effects on SOC stocks, while others collect soil carbon and ancillary data to provide a nationally consistent assessment of SOC conditions across the major land-use types. The SMNs in Brazil and Canada use a paired-site approach in order to detect the SOC response to specific land management (no-till in Canada and conversion from forest to agriculture in Brazil). These are stratified by ecoregion or typical farming system. Three out of eight national inventories have a grid design, and the remainder are stratified according to land use, soil type and climate regions.

Spencer *et al.* (2011) give a comprehensive overview of the statistical considerations to be taken into account for an SMN. The three possibilities are simple random sampling, stratified sampling or grid-based sampling. Although random sampling is conceptually the simplest option, it can be difficult to implement and carries the risk of leaving aside some regions. Grid-based sampling is a practical and efficient technique and generally results in a better estimation of the variable of interest and an even distribution across the whole domain. A stratified approach allows for allocation of a greater number of samples in strata with a higher variability in SOC stocks. Generally, samples are allocated randomly within strata. Strata can be defined according to major climate, land-use and soil-type combinations. Such an approach has the advantage that SOC stock changes can be linked directly to the categories used for reporting by the UNFCCC (see Ravindranath and Ostwald, 2008). Using the results of Century model runs, Spencer *et al.* (2011) discuss the statistical power of different attribution approaches for sampling points to the strata.

It has been shown that marking individual sampling sites with either a physical marker (e.g. ball marker 3M, Austin, Texas) or precise positioning using a Differential Global Positioning System (DGPS) is the most efficient in order to decrease the MDD for eventual re-sampling in the future (Fig. 16.1). Generally, a composite sample, which involves taking subsamples and bulking them, is taken according to a fixed spatial pattern (Table 16.2). Studies of subsampling error of monitoring sites are crucial for interpretation of results and changes (Arrouays *et al.*, 2012).

Error propagation

Error propagation methods have been used to estimate the contribution of the different variables required to calculate SOC stocks (C concentration, bulk density, stoniness and soil depth) (Goidts *et al.*, 2009). Overall, the spatial variability of topsoil SOC stocks is larger in grasslands than in croplands (Schrumpf *et al.*, 2011). Although the main source of uncertainty in the topsoil SOC stock varied according to scale, the variability of SOC concentration and of the stone content were the largest. When assessing SOC stock at the landscape scale, one should focus on the precision of SOC analyses from the laboratory, reducing the spatial variation of SOC, and use equivalent masses for SOC stock comparison (Goidts *et al.*, 2009).

Sampling depth

Organic layers at the soil's surface need to be sampled separately from the underlying

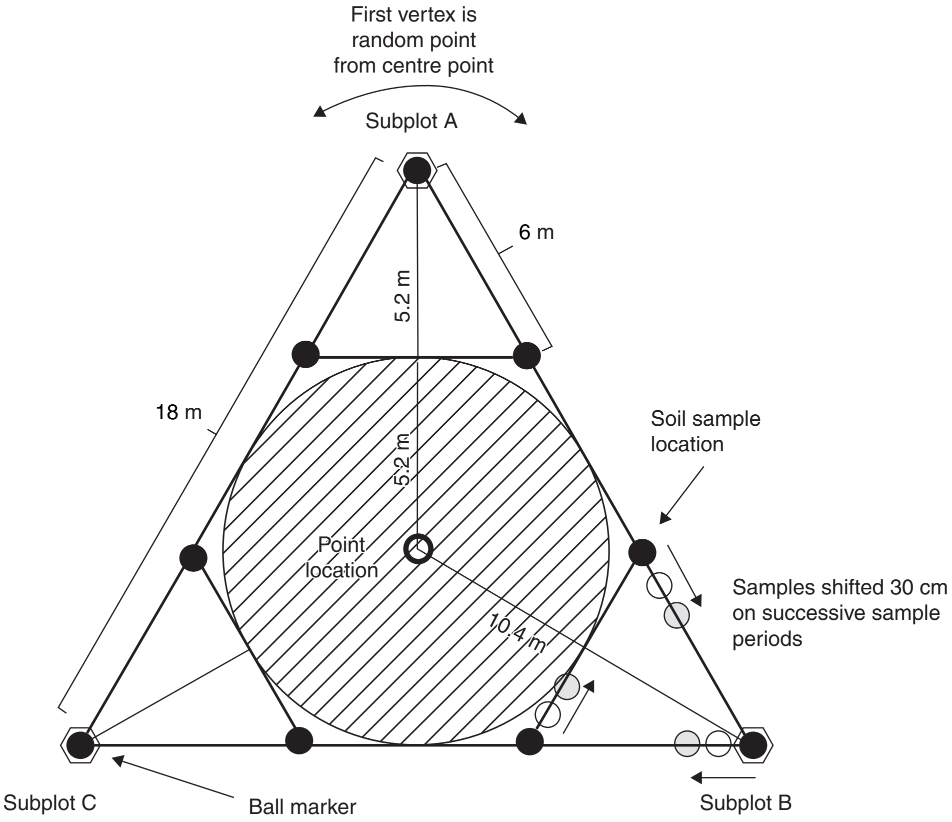

Fig. 16.1. Possible layout for a soil-monitoring site. (From Spencer *et al*., 2011, with kind permission of Taylor & Francis.)

organo-mineral soil. A common practice is to sample mineral layers both by depth increment in the site as well as by pedogenetic horizons in a soil pit, located in close proximity to the monitoring site (Arrouays *et al.*, 2012) or in the centre of the monitoring plot (Fig. 16.2). Sampling to depths greater than 20–30 cm is recommended (Table 16.2, also: Batlle-Bayer *et al.*, 2010; Schrumpf *et al.*, 2011), as adoption of too shallow a sampling depth may preclude the conversion to SOC stock on an equivalent mass per area basis (Ellert and Bettany, 1995), which is the recommended practice (Wendt and Hauser, 2013). Consideration of a fixed depth for reporting possible SOC changes will further ignore the effect of land-use change induced modifications in bulk density (e.g. compaction). Estimation of SOC stocks based on a definite soil mass per area, however, accentuates differences in sites and soil cores as compared to the fixed depth method, due to the negative relationship between SOC concentration and bulk density (Schrumpf *et al.*, 2011). For pragmatic reasons, the IPCC method for national inventories considers SOC stock changes expressed on a volume basis to 30 cm depth (IPCC, 2006; Ravindranath and Ostwald, 2008), which is a simplification (Batjes, 2011a; Wendt and Hauser, 2013).

Analytical procedures

Most organizations implementing SMNs use long-established laboratory methods, and these can vary greatly between and within countries (Pleijsier, 1989; De Vos and Cools, 2011). This diversity can pose problems when using results from existing SMNs (Cools *et al.*, 2006;

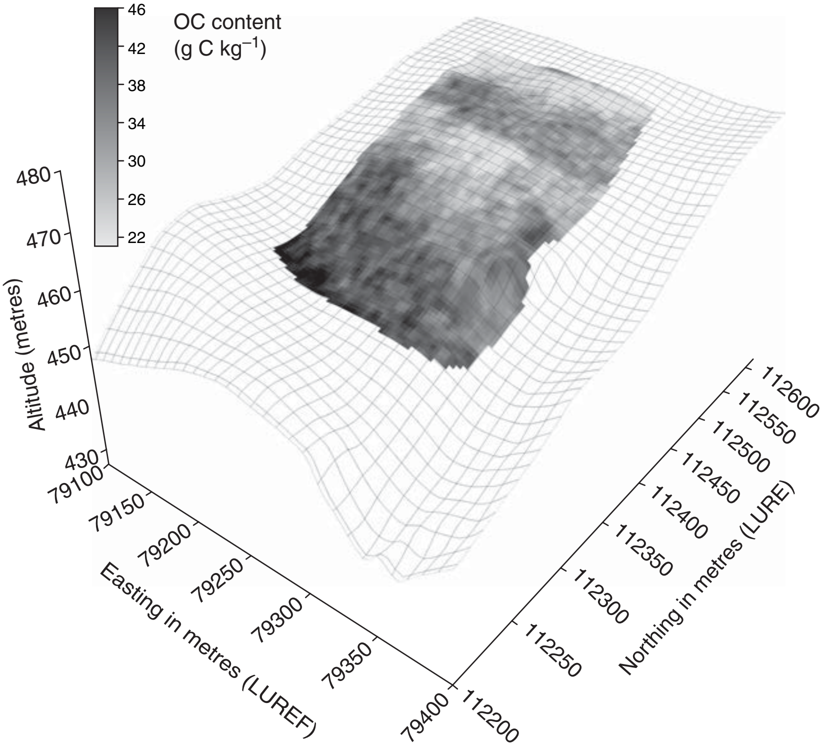

Fig. 16.2. Example of 'proximal sensing' approach for a field in Luxembourg. (From Stevens *et al*., 2010.)

Morvan *et al*., 2008). Adoption of a common standard (e.g. ISO TC 190 Soil Quality), however, would preclude comparison with earlier historic records, unless a set of reference samples could be analysed using both the new and 'old' methods. For example, dry combustion for SOC may be advocated rather than the more commonly used and cheaper Walkley and Black method, requiring the development of correction factors for incomplete oxidation (Lettens *et al*., 2007; Matus *et al*., 2009; Meersmans *et al*., 2009).

Harmonization may be defined as the minimization of systematic differences between different sources of environmental measures (Keune *et al*., 1991). There are some opportunities for harmonizing historic data obtained using different analytical methods, for example using regression analysis, but these are limited (Vogel, 1994; Cools *et al*., 2006; Panagos *et al*., 2013). Generally, a comprehensive comparison will require the establishment of benchmark sites devoted to harmonization and intercalibration of conventional soil analytical methods (Wagner *et al*., 2001; Kibblewhite *et al*., 2008; Morvan *et al*., 2008; Gardi *et al*., 2009). For each of these sites, key soil properties should be measured according to several (commonly used) analytical procedures, as well as the new standard reference method (e.g. ISO TC 190). In principle, this would allow comparison with results from earlier campaigns through the use of pedotransfer functions, which, inherently, will add uncertainty to the predicted values. There are no studies yet to assess how many calibration sites would be necessary for the world and how these sites may best be geo-located (Arrouays *et al*., 2012); interlaboratory comparisons remain critical here (van Reeuwijk, 1998; Cools *et al*., 2006).

Novel measurement techniques

Cost-effective techniques are needed to process the bulk of data derived from large soil-monitoring programmes. Visible and near infrared (Vis-NIR) and mid-infrared (MIR) reflectance spectroscopy have produced good results for the prediction of SOC content (McBratney *et al.*, 2006; Shepherd and Walsh, 2007; Viscarra *et al.*, 2010). Airborne imaging spectroscopy has been used for mapping topsoil properties (Ben-Dor *et al.*, 2008). This technique provides good results for mapping the SOC content in the plough layer of bare soils (i.e. in seedbed condition).

The prediction of topsoil SOC content from remotely acquired spectral data is generally based on an empirical approach. Reference soil analyses of samples collected in the field are related to the spectral information through a multivariate calibration model used to predict the SOC values at locations for which there are no measured SOC data (Stevens *et al.*, 2012). Several multivariate calibration models were developed to predict the SOC content in the plough layer of bare cropland fields in an airborne imaging spectroscopy scene of 420 km^2 in Luxembourg. For such large areas, the model performance depends strongly on the validation technique. The root mean square error of the most stringent validation procedure (excluding the fields used in the calibration) was equal to 4.7 $g\ C\ kg^{-1}$. Although this uncertainty is probably not good enough for the estimation of SOC stocks in individual fields, it can be used for regional mapping of SOC content and provides a unique insight into the spatial pattern of SOC content within fields (Fig. 16.2; Stevens *et al.*, 2010). In all cases, however, conventionally measured SOC (dry combustion) in reference laboratories is necessary to calibrate the new techniques, and to build spectral libraries needed for the extension of spectral measurements in unsampled areas (Shepherd and Walsh, 2007; Bartholomeus *et al.*, 2008; Terhoeven-Urselmans *et al.*, 2010). Further, as techniques and standards for soil analyses are evolving continuously, it is good practice to preserve soil samples from SMNs so that they may be re-analysed in the future (McKenzie *et al.*, 2002; Shepherd and Walsh, 2002; Arrouays *et al.*, 2012).

Upscaling and Modelling

Typically, soil-monitoring activities encompass several decades of measurements (which implies long-term commitment from funding agencies and researchers). Appropriate data management tools are required to store the various data, check for errors and retrieve selected data for sharing and analysis (Cools *et al.*, 2006; Lacarce *et al.*, 2009; Batjes *et al.*, 2013). The range of soil and ancillary data collated through SMNs and similar field sampling programmes should be stored in a (freely accessible) information system to support geostatistical analyses and modelling (see Chapter 17, this volume). At present, however, external access to SMN data is often restricted to the metadata (Morvan *et al.*, 2008; Panagos *et al.*, 2013), thereby greatly reducing their value to the scientific community and society.

In particular, there is a need for globally consistent protocols and tools to measure, monitor and model SOC changes and GHG emissions so that funding agencies and other organizations can assess uniformly the possible impacts of land-use interventions and climate change, as well as the associated uncertainties, across the range of world climates, soils and land uses. An example of such an integrated facility is the online Carbon Benefits Project tool developed for the Global Environmental Facility (GEF). It includes both empirical as well as process-based modelling approaches, which can be chosen based on the user requirements and available data through a user guidance module (Milne *et al.*, 2010, 2012). Whether monitoring or modelling SOC dynamics/processes, the key issue is how to address complex issues of spatial and/or temporal variability at the scale of interest (Cerri *et al.*, 2004; Maia *et al.*, 2010; Smith *et al.*, 2012). Opportunities include the use of ancillary data, scale-specific methods, development of spectral libraries, digital mapping of soil carbon and better integration of remote-sensing technologies into empirical and simulation SOC models (Grunwald *et al.*, 2011; Croft *et al.*, 2012; Minasny *et al.*, 2013).

Conclusions

Based on the materials reviewed here, some basic methodological requirements and recommendations can be proposed for 'good SOC-monitoring practice' to support scientific and policy decisions. These include: (i) the provision of long-term continuity and consistency under changing boundary conditions, such as biophysical site conditions, climate change, methodologies, socio-economic setting and policy context; (ii) adoption of a scientifically and politically (e.g. for UNFCCC) appropriate spatial and temporal resolution for the measurements; (iii) ensuring continuous quality assurance at all stages of the measurement and monitoring process; (iv) measurement/observation and documentation of all potential drivers of SOC and GHG change; and (v) georeferenced samples, collated through SMNs, archived and the associated (harmonized) data made accessible through distributed databases to enhance the value of the collated data for multiple uses. In addition to this, SMNs should be included in a broader cross-method validation programme, ultimately to permit spatially and temporally validated comparisons both within and between countries.

The most common sampling design of SMNs aimed at monitoring regional/national SOC stocks is either stratified (according to soil/land use/climate) or grid based. Large countries with a low sampling density (<1 site per 100 km^2) generally prefer a stratified design so as to include all important units. The (expected) variability within these units should be determined to assess the optimal number of samples for each stratum. Such an approach will allow a statistical analysis of trends in SOC stocks for the soil/land use/climate units under consideration as an alternative or test for process-based models.

The establishment of SMNs poses various scientific, technical and operational challenges. The former are being addressed by various groups, such as the Soil Monitoring Working Group established in 2010 by the International Union of Soil Sciences (IUSS). From an operational point of view, to implement an integrated monitoring system it will be crucial to overcome initialization costs and unequal access to monitoring technologies. For the developing countries, this will require international cooperation, capacity building and technology transfer.

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