How can soil monitoring networks be used to improve predictions of organic carbon pool dynamics and CO2 fluxes in agricultural soils?

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Abstract

As regional and continental carbon balances of terrestrial ecosystems become available, it becomes clear that the soils are the largest source of uncertainty. Repeated inventories of soil organic carbon (SOC) organized in soil monitoring networks (SMN) are being implemented in a number of countries. This paper reviews the concepts and design of SMNs in ten countries, and discusses the contribution of such networks to reducing the uncertainty of soil carbon balances. 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 soil carbon condition across the major land-use/soil type combinations. The former use a single sampling campaign of paired sites, while for the latter both systematic (usually grid based) and stratified repeated sampling campaigns (5–10 years interval) are used with densities of one site per 10–1,040 km². For paired sites, multiple samples at each site are taken in order to allow statistical analysis, while for the single sites, composite samples are taken. In both cases, fixed depth increments together with samples for bulk density and stone content are recommended. Samples should be archived to allow for re-measurement purposes using updated techniques. Information on land management, and where possible, land use history should be systematically recorded for each site. A case study of the agricultural frontier in Brazil is presented in which land use effect factors are calculated in order to quantify the CO2 fluxes from national land use/management conversion matrices. Process-based SOC models can be run for the individual points of the SMN, provided detailed land management records are available. These studies are still rare, as most SMNs have been implemented recently or are in progress. Examples from the USA and Belgium show that uncertainties in SOC change range from 1.6–6.5 Mg C ha−1 for the prediction of SOC stock changes on individual sites to 11.72 Mg C ha−1 or 34% of the median SOC change for soil/land use/climate units. For national SOC monitoring, stratified sampling sites appears to be the most straightforward attribution of SOC values to units with similar soil/land use/climate conditions (i.e. a spatially implicit upscaling approach).

Keywords Soil monitoring networks - Soil organic carbon - Modeling - Sampling design

Introduction

The soil is one of the largest pools in the global carbon cycle, and there are still large uncertainties regarding its dynamics. For cropland and grazing land, soil is by far the dominant C pool in the ecosystem and of most interest with respect to CO_2 emissions and removals. These systems, particularly croplands, are intensively managed and the choice of crops and the management options have been demonstrated to have a large impact on the SOC dynamics and CO_2 exchange with the atmosphere (Paustian et al. 1998; Lal et al. 2007; Smith et al. 2006, 2010). Hence quantifying soil CO_2 exchange with the atmosphere is very important for national greenhouse gas reporting and implementing greenhouse gas mitigation policies that include soil C sequestration. Different methods exist for estimating CO_2 fluxes from soils: 1) measurement-based assessments of SOC mass dynamics, 2) direct measurement of CO_2 fluxes and 3) modeling of SOC dynamics using biophysical and land use/management data expressed at regional scales. While direct measurement of CO_2 fluxes, for example using eddy covariance, is well developed and several regional networks exist (Baldocchi 2008), their cost and infrastructure requirements limit the number of measurement locations possible and thus they primarily fulfill an ecosystem research function. However, Law et al. (2006) illustrate a strategy for upscaling where the measurements of carbon fluxes (flux towers) and pools (stock changes in the soil and biomass determined from plots) are used to parameterize and test biophysical models quantifying the terrestrial carbon cycle of a forested region in the Pacific Northwest (USA). As agricultural systems are intensively managed, agricultural measures governed by socio-economic factors are paramount as input to biophysical models (e.g. amount of manure applied or residue returned after harvest). In order to synchronize the scale at which both socio-economic and biophysical data are available, the field is often chosen as the intrinsic scale for modeling considering input and process rates to be homogenous (Wu et al. 2006). These authors propose that extrapolation to the scale of interest, such as region with similar soils, climate and land management is then based on a spatially implicit approach where variables, parameters or outcomes of model runs for the intrinsic unit are attributed to areas that have similar biophysical and socio-economic characteristics. This implies that soil monitoring networks should provide information to parameterize and test biophysical models at the field scale and that the total set of individual points should cover as much as possible the variation in soil/climate/land management encountered at the regional scale.

An extensive review of European soil monitoring efforts, including recommendations on the sampling and testing protocols, was carried out in the ENVASSO project (Morvan et al. 2008). A soil monitoring network (SMN) was defined by Morvan et al. (2008) as 'a set of sites/areas where changes in soil characteristics are documented through periodic assessment of an extended set of soil parameters'. Most of these networks are either in the planning stage or have been sampled once, and therefore can at this point only be used to determine SOC stocks rather than quantify SOC dynamics. The density of the networks in most European countries is high with a median coverage of 300 km^2 for each monitoring site (Saby et al. 2008). Still, Saby et al. (2008) demonstrated that lumping or simple averaging (in the sense of Wu and Li 2006) of the point SOC stocks would not detect significant changes in SOC pools at the country level within the next 10 years. Similarly, Yan and Cai (2008) used a national soil survey database to estimate that at least 1,000 sites for croplands or 4,000 sites for all types of land use would be required to detect a change of 5% of the SOC stock for China at a 95% confidence interval. Spatially implicit extrapolation of the outcomes of models parameterized at the monitoring sites to the regional scale is a more promising technique (Wu and Li

2006). Ogle et al. (2007) are among the few authors who directly used observed SOC dynamics in a modeling exercise. They compared modeled SOC dynamics obtained by the Century model with observed trends from 47 long term experiments with different cropping and management practices in the US in order to assess the uncertainty as a result of model parameterization and algorithms. González et al. (2008) did a similar exercise in México running the ROTHC-26.3 model on short time observations.

The objective of this paper is to review how SMNs can contribute to the estimation of the dynamics in regional SOC pools and CO2 fluxes in several different countries. Based on this review, we provide recommendations for the design of SMNs and the measurements collected at each sampling point.

This paper is a follow-up of an informal workshop on SOC monitoring organized during the International Symposium on 'Soil organic matter dynamics: Land Use, Management and Global Change' at Colorado Springs, Colorado, USA, July 6–9, 2009. We sent a questionnaire to the participants from the different countries represented at the meeting regarding the use of the data from SMNs an used examples of upscaling SOC conditions to regional/national estimates for agricultural soils.

Review of different soil monitoring networks

Design of the soil monitoring networks

The details of the SMN design in ten different countries are given in Table 1. The networks in Brazil and Canada cover specific land management conditions often using a paired site approach with a well-documented history of the management change. Such networks will serve as empirical database to detect the SOC response to land use/land management change. Most networks (7 countries out of 10) are designed for national inventories of soil carbon stocks and cover the variation in soil, land use and climate conditions over the entire country. The SMN in China consists of 1,081 sites distributed over six regions that were originally designed for soil fertility monitoring (Pan et al. 2010). The objectives of these networks are wider as for example stated for the Australian SMN: 1) a consistent assessment of soil carbon condition across the major land use/soil types used for agricultural production, 2) identifying the potential for management strategies to increase soil carbon, 3) quantifying the carbon inputs in agricultural systems based on perennial vegetation, 4) development of rapid methods for determining bulk density and organic carbon fractions, and 5) providing data for national greenhouse gas accounting. The design of both types of SMNs (i.e. land management effect and national or regional soil carbon inventory) is discussed separately below and some examples of both types for agricultural systems are given. The details of all SMNs are given in Tables 1 and 2.

SOC response to land use/land management change

These networks generally contain a limited number of sampling sites (96 in Canada and 352 in Brazil, Table 1). They are stratified by ecoregion or typical farming system within a region in order to demonstrate the effect of land management system by comparing paired sites. The SMN in Brazil was specifically designed to quantify the cropping factors in the IPCC guidelines (IPCC 2006) in order to quantify greenhouse gas emissions from land use change in the largest agricultural frontier (i.e. the Brazilian Amazon; Maia et al. 2010). Within 11 ecoregions (defined as areas with a homogeneity in conditions determining SOC stocks), two municipalities were selected and within each municipality 16 paired sites were identified. The criteria for choosing the paired sites were the knowledge of management practices since conversion by the farmer and the possibility to sample a paired site under natural vegetation within 0.2 km. Samples were collected from full and zero tillage annual crops as well as from perennial crops.

National or regional SOC monitoring

Three out of eight national inventory networks (Germany, Mexico, Sweden) have a grid design and the remainder (Australia, Belgium, New Zealand, USA) are stratified. This is similar to the European networks reported in the ENVASSO project of which 43% have a grid sampling design (Morvan et al. 2008). The sample density of the seven national SMNs and the regional SMN in China varies between one site for 10 km² to 1,040 km² (Table 1). As was found in the ENVASSO project, the grid sampling design has the advantage of giving unbiased estimates (Morvan et al. 2008). However, the risks of grid sampling are that specific land use/soil combinations are not represented. Therefore, it is not surprising that the large countries with a large scale soil/land use variation and a low sampling density (>100 km² per site) opt for a stratified approach where units with a specific soil/land use/climate combination are sampled. Apart from the USA and Australia, the sample density is higher (10–202 km² per site) than the median density of European networks (300 km² per site, Morvan et al. 2008).

Three examples of the SMNs used for national SOC inventories (NZ, Australia, USA) are given below. The SMN in New Zealand is the oldest and the network has gradually been extended. Some of the older profiles in this network were originally not intended to be used for SOC inventories. Instead they were analysed to construct and verify soil maps.

The main SMN in New Zealand builds on the National Soils Database (NSD), a soil pedology-based network managed by government research agencies since the 1930s. The original intent of the NSD was as a resource for the development of agricultural (mainly pastoral) lands and so the spatial coverage reflects this bias. which gradually is being rectified to meet the needs of environmental management agencies. Limited re-sampling of this network has been occurring since 1992, contributing to studies of long-term changes in SOC (Schipper et al. 2007). A secondary SMN is provided by the “500 Soils” project, which began in 1995 as a nationally integrated local government initiative to monitor the effect of land use on soil quality. There are now ~800 sites nationally, mainly representing low altitude agricultural and production forestry environments, similarly to the NSD (http://www.mfe.govt.nz/issues/climate/lucas/). However, in contrast to the NSD, the sampling protocol for this SMN is based on composite samples of topsoils (0–10 cm) along field transects. Thus it has the potential to provide a limited empirical cross validation for the NSD.

The Australian Soil Carbon Research Program (SCaRP) is funded by the federal Department of Agriculture, Fisheries and Forestry (DAFF) under Australia's Future Farming initiative. The SCaRP started in 2009 and consists of eight geographically distinct research projects across all States and the Northern Territory, run by federal and state agencies and universities, covering over 40 agricultural regions (SE South Australia cereal sheep and beef & SW New South Wales perennial grasslands; SW New South Wales cereal, sheep and beef; Victoria dairy, sheep, beef; Northern Territory rangelands; Queensland cereals and sugar; New South Wales cereals, cotton, sheep and beef; Tasmania vegetables and dairy) plus one integrating project lead by CSIRO in order to harmonize sampling and data analysis. The majority of sampling sites are rainfed cereals and perennial pastures, with high rainfall cotton, sugar cane, dairy and vegetable systems also represented. Sampling designs vary from multiple samples collected at multiple points at a single site (normally a farmer's field) characterised by a specific soil type and management system, to replicated field trials and paired sites. The initial 3 year program focuses on the acquisition of SOC data in mass units at the regional level. This priority was chosen considering the influence of climate variability on agricultural production and the slow rate of change of soil organic carbon in many Australian agro-ecosystems.

The SMN in the USA is planned for both crop and grazing lands with sampling across the major climate and soil types. Individual monitoring sites will be stratified by land use (i.e. cropland and grazing lands) and Major Land Resource Area (MLRA). MLRAs are regions with relatively similar climate and soils, as well as similar land use systems (USDA-NRCS 1981). Selection of sites is based on detecting a change in SOC over a 5–10 year period, using a combination of evenly distributing a minimum number of samples per MLRA, and then subdividing the remainder using Neyman's optimal allocation method that allocates more sample points to areas with greater C stock variability (Cochran 1977). In total, 170 MLRAs cover the main types of cropland and grassland in the USA. A minimum of three sites and a maximum of 118 sites in an MLRA/land use combination are proposed to cover the variability in SOC stock, yielding a total of 1,962 sites on grassland and 3,038 in croplands. All sites are located at National Resource Inventory (NRI) points where the land use and some management practices (e.g. crop species, irrigation) have been recorded yearly since 1979 (Nusser and Goebel 1997).

Parameters recorded at each site

SOC response to land use/land management change

Soils are sampled at depth intervals (e.g. 0–5, 5–10, 10–20, 20–30 cm) during a single campaign (Table 1). In general, several points per site are sampled and individual samples are analysed. These SMNs compare sites with different land management practices between them, but do not aim to follow trends in SOC in single sites over time. Therefore, geo-referencing the sample points within the sites or archiving the samples is not crucial. As illustrated above in the Brazilian example, the selection of the paired sites is based on specific land management practices (Maia et al. 2010).

National or regional SOC monitoring

The soil sampling procedures of national SOC monitoring networks are quite similar in the different countries. They are consistent with the recommendations of the ENVASSO project: at least four subsamples for which the exact location is known, stocks to be calculated for at least 0–15 cm and 0–30 cm, archiving of the samples (Table 2; Morvan et al. 2008). The points are geo-referenced using a GPS with an accuracy of ca. 10 m and in Belgium, Germany and the US the exact position of the site is given by a buried electronic marker (cm-level precision of a fixed point in a micro-site). Samples are composites of 4–5 subsamples in an area of c.100 m^2 and in general fixed depth intervals are sampled at least until a depth of 30 cm. All countries report that they archive the samples. This is crucial both as a quality control measure and to provide opportunity to better understand observed changes as new techniques to measure SOC and otherwise characterize SOM become available in the future (Trumbore 2009).

Information on land management practices such as crop grown, yield, fertilization, manure applications and tillage practices is not routinely gathered in most cases (Table 2). Annual records are kept in China for each individual site, whereas in other countries the land management information is extracted from agricultural databases that are not specific to the sampling locations. The information provided in the National Resource Inventory (USA), where information is collected repeatedly at the same exact locations, is the most complete (Nusser and Goebel 1997). Using the NRI points as sample points in the SMN guarantees a consistent time series of both SOC and site land use and management data.

Analytical techniques

The most commonly used SOC analysis technique is dry combustion using a CN analyser, although wet oxidation using the Walkley and Black technique is still used in some cases, mainly when the network was started some time ago (Walkley and Black 1934; Table 2). Some countries are developing newer analysis techniques for determining total SOC and/or SOC fractions such as infrared spectrometry either using the near infrared (NIR) in Mexico and Brazil or the mid-infrared (MIR) in Australia (Ludwig et al. 2008). The distribution of different SOC fractions making up the total organic C pool better represents the individual SOC pools of process-based models than the sum of these pools. However, relating the conceptual SOC pools used in the models to analytical SOC fractions still remains a challenge (Zimmermann et al. 2007). In general, a suite of other soil parameters is also determined on the samples (Table 2). Bulk density and rock fragment content are determined for all sites in all countries. Although it is quite straightforward to measure bulk density, traditional gravimetric techniques are quite slow and the spatial variability in bulkdensity of agricultural soils is large. Hence, gammaspectrometry techniques are proposed to be tested in Australia as a non-destructive and efficient alternative.

Upscaling the SOC conditions from the site to the soil/land use/climate unit

SOC response to land use/land management change

Paired sites (native/cropland and native/grassland) in the Brazilian Amazon have been analysed both in 1985–1990 and more recently using linear mixed-effect models. The introduction of zero tillage has a measurable effect on the stock change factors, showing an increase in stocks to values higher than in native savanna and tropical forest vegetation (Maia et al. 2010). These stock change factors will then be extrapolated to calculate the impacts of land use change on GHG emissions from Rondonia and Mato Grosso states (about 1.2 million km2, i.e. 23% of the Brazilian Amazon Region). No till systems in Brazilian Savanna vegetation increased SOC stocks by 1.08 ± 0.06, while full tillage reduced the SOC stocks by 0.94 ± 0.04 (Maia et al. 2010).

National or regional SOC monitoring

Empirical models for SOC in soil/land use/climate classes

Empirical models have been developed to attribute a SOC stock (Mg C ha -1) to soil/land use classes in New Zealand and Belgium (Tate et al. 2005; Meersmans et al. 2010). Such models produce a SOC stock for all soil land use classes together with a measure of uncertainty. The geo-referenced SOC data were used to determine the average soil C for each combination using a General Linear Model. For New Zealand, this model has been enhanced by inclusion of an “erosion index” (accounting for slope × rainfall interactions) and a correction for spatial correlation between data points. It is assumed that the SOC values in the soils database represent equilibrium values for each soil/climate/land cover combination (Tate et al. 1997). The SOC values obtained from the repeated sampling (every 5 years) are combined with an inventory of the land use giving a SOC pool for each unit that can be aggregated to the national level. SOC values from the SMN network are incorporated into the national soil carbon monitoring system (Soil CMS) by stratifying the New Zealand land mass into 39 combinations of soil class, climate and land cover, describing 93% of the land area (Tate et al. 2005). For Belgium, Meersmans et al. (2010) found that a multiple linear regression model was able to predict SOC concentrations for the soil/land use/climate units with a RMSE of 17% of the mean using the stratified sampling approach specified in Table 1.

Predicting changes in SOC stocks for soil/land use/climate units using simulation models

High precision data of real value for model parameterization and testing can probably only be obtained in controlled field trials. In a recent paper Johnston et al. (2009) review the insights into processes and contribution to model parameterization that the recording of all yield, crop rotation, fertilization, residue and manure data for the different long term field trials in Rothamsted have provided. Unfortunately, such field trials are scarce and do not cover all agricultural practices encountered in a region or a country. Therefore, SMNs are an alternative for providing input data for the sampling sites. The SOC evolution for these sites can then be applied to soil/land use/climate units using a spatially implicit approach (Wu et al. 2006). Apart from the site attributes (i.e., climate, soil type, land use history and management), Andrén et al. (2008) used the SOC values from their SMN in croplands as baseline SOC values for the ICBM model to predict the SOC dynamics in Swedish agricultural soils for the period 1990–2004. The model results will shortly be confronted with the evolution of the SOC in the SMN for which now both a 1995 and 2005 sampling campaign are available. Samples from the SMN in the USA will constitute an independent dataset from model development and parameterization that can be used for validation purposes and uncertainty assessment of SOC stock changes. Although most countries are reporting land use and management data, the most comprehensive system is the NRI in the USA that started in 1979 and consists of c. 800,000 sites. Expansion factors have been calculated that allow upscaling point results to regional or national SOC stocks (Nusser and Goebel 1997). An empirically-based uncertainty estimator will be developed from statistical comparisons between the measured SOC stocks and modeled results (Ogle et al. 2007). Ogle et al. (2007) used a similar approach to compare SOC stocks predicted by the Century model (Parton et al. 1994) with observed SOC stocks in 872 treatments of 47 long term experiments. The linear mixed-effect model showed that on average Century under-predicted the observed SOC stocks. The greatest deviations were for model underestimates of treatments with organic amendments by 6.1 Mg C ha−1, hay or pasture in the rotation by 6.5 Mg C ha−1 and no-till by 1.6 Mg C ha−1. There were interactions between hay/pasture in the rotation and organic amendments as well as set-aside and modeled SOC stocks.

When the first sampling dates back 25 years (UK, Bellamy et al. 2005; New Zealand; Schipper et al. 2007; China and its Jiangsu province, Liao et al. 2009; Pan et al. 2010) or even 50 years (Belgium; Goidts and van Wesemael 2007), data on land management for the individual sites are not available. However, simpler modeling approaches using aggregated input data still provide meaningful SOC trends over such long periods. A simple single pool SOC turnover model was used to predict the average decomposition constants for all c. 2,500 mineral soil profiles available for England and Wales (Kirk and Bellamy 2010). The results showed that climate change could not explain the changes in overall decomposition constant and that, therefore, the effects of changes in land use and management were probably dominant. The RothC model (Coleman and Jenkinson 1999) was applied to soil/climate/land use combinations in Belgium using average input data for these units and the results were compared to inventory data from the 1960s that were re-sampled in 2006 (van Wesemael et al. 2010). The results showed that the largest changes in SOC stocks (losses of more than 50 Mg C ha−1 in poorly drained grasslands and gains of more than 30 Mg C ha−1 in grasslands in the low mountain ranges) occurred in units following episodic land management practices i.e., drainage after land consolidation and historic (between 1920–1950) conversions of cropland to grassland. The model results were compared to the average SOC change obtained from more than 600 re-sampled profiles (0–30 cm) most of them belonging to the SMN of southern Belgium resulting in a RMSE of 11.72 Mg C ha−1 (Table 1). The median uncertainty amounted to 34.5% of the SOC change for the units. As the RothC model is validated for croplands and grasslands in temperate climates, van Wesemael et al. (2010) used the default decomposition rates and initialized the model using the SOC data from 1960 with a fixed distribution over the model SOC pools. The input data consisted of clay content, monthly carbon input from crops and manure as well as monthly temperature, precipitation and potential evapotranspiration. As long term data series of crop input data, manure data and climate data for each profile are difficult to obtain, they ran the model using averages for agricultural regions. Running a SOC dynamics model on the input data of the individual profiles of the SMN would certainly decrease the uncertainty.

Conclusions and recommendations

The intrinsic scale required to calculate the change in SOC stocks of agricultural soils is the field for which a consistent set of management data (e.g. residue returned to the soil or manure spread) and biophysical variables (initial SOC values, soil texture, climate data) can be collected. The main objective of soil monitoring networks (SMN) is to upscale this information to the scale of interest i.e. a region with similar soil and management or even aggregated to the agricultural soils of an entire country. As it is not possible to sample all combinations of land use and soil type within a region and collect enough samples with a statistically significant variance, lumped approaches to upscale the SOC conditions from SMNs are in most cases not able to reveal significant trends in regional or national SOC stocks within a period of 5–10 years. Even if they do, the attribution of observed changes to specific driving factors as well as the reliability for such trends are difficult to establish. Hence, spatially implicit approaches are often used to attribute SOC conditions at the SMN sites to similar soil/land use/climate units. The review of SMNs in ten countries revealed that two objectives can be distinguished for upscaling: 1) determining the SOC response to land use/management change, and 2) monitoring SOC changes at the regional/national scale. The former approach is based on a statistical comparison of SOC data from a single campaign between paired sites with well-documented management practices. The latter approach uses SOC data from single sites that are re-sampled (or to be re-sampled) at 5–10 years intervals for modeling SOC stocks using either empirical models to predict the SOC value of a specific soil/climate/land use unit or simulation models to predict the SOC change in such units. An example from Belgium demonstrates that the RMSE of an empirical model reached 17% of the mean SOC stock of the soil/land use/climate units, while a simulation model predicts changes in SOC stocks for the same units with a RMSE of 11.72 Mg C ha -1 corresponding to 34% of the median SOC change over a period of 50 years. Although the number of studies on upscaling the results of SMNs is still very limited, some recommendations on design, sampling and analytical procedures can be given.

Adequate pairing is required to clearly demonstrate that measured differences are due to a management effect and not to confounding factors. Collection of detailed land management records is essential to prove that the initial conditions for both sites were similar and that the driving forces for the observed change are known. Multiple samples need to be analysed (either within site or using replicate sites) for statistical testing of the treatments.

For single sites that will be re-sampled over 5–10 year periods, composite samples are adequate instead of replicating the analysis for each site. The exact position of composite samples (4–10 sub-samples) should be recorded an preferentially marked in the field (e.g. buried antennas) as within site variability can be large and even larger than expected trends over time. For historical trends, soil samples should be available from archives in order to avoid biases induced by changes in analytical procedures over time. This is of great importance, since observed differences between sampling occasions must not be due to differences in, e.g., calibration of analytical equipment. Crop/grass production data as well as other data on agricultural practices is required when the sites are used as input for process-based models.

For both paired and single sites, samples should be taken at multiple fixed depth intervals (to at least 30 cm). Bulk density, rock fragment content and large pieces of organic debris should also be determined. These parameters are essential to convert SOC concentrations of the fine earth into SOC stocks and to correct for the bias of soil compaction on SOC stocks over time. Unfortunately, bulk density and rock fragment content were not always determined in the past. Even when samples have been archived, bulk density cannot be determined on these disturbed samples, and rock fragments and coarse organic debris are often discarded after sieving. Novel techniques based on gammaspectrometry for bulk density and Mid Infra Red Reflectometry for SOC fractions are being calibrated in Australia. These techniques allow to sample and analyse more efficiently and thus account for the large variability in bulk density as well as better validating SOC models that already distinguish different SOC fractions. Apart from the total organic carbon (TOC), particulate organic matter (POC) larger than 250 µm and 53 µm, char and humus (the difference between TOC and POC) are considered.

The most common sampling design of SMNs intended to monitor 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 km²) generally prefer a stratified design in order not to miss important units. It is recommended to analyze the (expected) variability within these units in order to determine the optimal sample number. Such an approach will allow a statistical analysis of trends in SOC stocks for the soil/land use/climate units as an alternative or test for process-based models.

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Table 1 Summary of soil monitoring networks and sample design

	Belgium	Germany	Mexico	New Zealand	Sweden
Objective	National SOC monitoring	National SOC monitoring	National SOC monitoring	National SOC monitoring	National 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, though coastal/lowland/intensive agricultural regions are best represented	Cropland c. 3 Mha.
Starting date	National Soil survey 1950–1970; resampled 2004–2007	November 2010	started in 2003; each year 1/5 of the sites will be re-sampled	National soils database from 1938. Land use and carbon analysis system (LUCAS) started in 1996[a]	Full scale in 1995, some data from 1988
Site density (km^2 per site)	18 km^2	64 km^2	78 km^2	202 km^2	10 km^2
Site selection	stratified	Grid	Grid	stratified	Grid
Units	Re-sampled sites in soil/land use/climate units with i) at least 30 NSS profiles and ii) a low minimum detectable difference	N/A	N/A	According to seven soil classes including six IPCC categories. sample points were selected to be included in the National Soils Database	N/A
Soil sampling					
Sub-samples	composite sample of 5 points within 4 m radius	composite	composite sample	Single 1.5 m pedological pit at each site	composite samples of 6–20 cores in 10–20 m^2 sites; subsoil: 6 cores
Depth	0–30 cm and 0–100 cm for 183 sites (out of 427)	0–10; 10–20; 20–30; 30–60 and 60–100 cm	soil cores of 0–30 cm and 30–60 cm	variable, sampled by soil horizon; in 2009, 1235 samples to 30 cm	0–20 cm topsoil; 40–60 cm subsoil. In 2003: 500 samples 0–20, 20–40 and 40–60 cm
Frequency	Once, but can be re-sampled in future if funding is available	every 10 years	every 5 years	Sites originally sampled between 1938 and 2004; 83 sites re-sampled between 1992–2004, 14 of these re-sampled again. Re-sampling is ongoing	1995 and 2005 done, will be repeated every 10 years

	USA	Australia	Brazil	Canada	China
Objective	National SOC monitoring	Baseline SOC for land use/soil combinations; SOC response to land use/management change	SOC response to land use/management change	SOC response to land use/management change	Regional SOC monitoring
Region covered	Cropland and grazing land in the USA	Cropland and grazing land in all states of Australia and the Northern Territory, NW Australia is not represented	Rodônia and Mato Grosso, annual crops: 16, perennial crops: 8, grassland: 40, Native vegetation 33	No-till sites in Saskatchewan province (n = 96)	Northeast (120 sites), North (241), East (356), South (119), Northwest (148), Southwest (97)
Starting date	planned	July 2009	2007	1997	78% started before 1985 and 87.5% continued until at least 1996
Site density	croplands: 438 km²; grazing lands: 1,040 km²	8 projects covering c. 40 agricultural sub-regions. Total number of locations is not known at this time.	N/A	N/A	N/A
Site selection	stratified	stratified	stratified	stratified	stratified
Short description	National Resource Inventory (NRI) points to be resampled in each Major Land Resource Area	Single point sites (min 25) covering major land management practises for each unit (soil type and rainfall)[a], paired sites	11 ecoregions from overlay of geology, geomorphology, climate, soil and vegetation. Within each region 2 municipalities for 16 paired sites, native vs. grassland or cropland	Paired-sites on no-till network on soil great group/agro-climatic region basis of Saskatchewan	Monitoring sites in typical farming systems within the regions, originally for soil fertility monitoring
Soil sampling					
Sub-samples	Triangle of 18 m sides centered on the NRI point. Three core composites samples on smaller triangles starting at corners of the large triangle	For 95% of sites a single composite sample. For 5% of sites individual soil samples are to be kept separate and geo-referenced	Square of 100[b]100 m with 5 soil pits (50[b]50[b]50 cm) in centre and on corners	Composite of 6 sub-samples on 4 [b] 7 micro site	composite sample of 5 to 20 subsamples depending on the size of the site : minimum area 1/30 ha
Depth	Cores are taken until 75 cm and subdivided in 10 cm slices. Litter (if present) to be sampled separately	three soil depth layers (0–10 cm, 10–20 cm, 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 topsoil
Frequency	Each point will be sampled every 5–10 years	Once, but can be re-sampled in future if funding is available	Once	sampled in 1997, 1999, 2005 and 2010	annual sampling from 2010

Table 1 continued

[a]LUCAS network: http://www.mfe.govt.nz/issues/climate/lucas/
[b]For consistency across the program the Australian Land Use and Management (ALUM) Classification is used http://adl.brs.gov.au/mapserv/landuse/index.cfm?fa=app.classes&tab=classification

Table 2 Summary of soil monitoring networks: analytical methods, site information and integration in greenhouse gas accounting

	Belgium	**Germany**	**Mexico**	**New Zealand**	**Sweden**	**USA**	**Australia**	**Brazil**	**Canada**	**China**
Analytical methods										
SOC	Walkley and Black with 1.3 correction factor	Total carbon analyser (CN), Carbonate after Scheibler	Total Carbon analyzer, calibration of NIRS method	Walkley and Black prior to 1970, LECO furnace after that	LECO CHN analyser	LECO CHN analyser	TOC and fractions by MIR spectroscopy, SOC fractions - POC – >53 µm fraction; Char	LECO CN analyser	Total carbon analyser(CN), Carbonates only when present	Walkley and Black
Other parameters	1950–1970 samples: texture, total N, Fe oxides, CEC, total P	Soil N, P, K, soil texture, pH	soil texture	texture, colour, structure, pH, total N, total P, CEC, P retention, base cations,	Texture at first, but later lots more	texture, pH, particulate organic matter, inorganic C,		texture, pH, N, H+Al, microbial biomass Cand N, macronutrients	soil texture	Soil N, P, K, NH4, available P
Correction for rock fragments	yes	yes	yes	yes	Not as standard, but only when data are used for modelling	yes	yes	yes	yes	mostly not
Bulk density	3 cores of 100 cm^3	yes	yes	yes	No; PTF based on C contents are used	yes	gammaspectrometry techniques being developed	yes	yes	required, but missing in most sites
Site information										
Land use history	unchanged from 1950	especially on sandy soils	known	some	No	Land use history before 1982 from pre-NRI histories (Brenner et al. 2005)	Land use history, including crop and grazing management	known since conversion from natural vegetation	land use history reconstructed	cropland
Crops grown each year	National database for crops grown each year in each field	Questionnaire to the farmers	known	current vegetation at time of sampling	will be recorded	Recorded in NRI	including multiple crops	soybean with millet or sorghum; perennial	crops grown and residue management, occurrence of hail storms	consitent for a single site
Fertilizer and manure applied	Not available for individual fields	Questionnaire to the farmers	when applicable	some	No	Recorded in NRI	annual N application	no	yes	known application of fertilizer and manure
Crop yield	Not available for individual fields	Questionnaire to the farmers	biomass of grassland is regularly determined	No	No	Recorded in NRI	annual yield including residue removal	no	no	annual data
Tillage intensity and depth	Not available for individual fields	Questionnaire to the farmers and if possible in the field	not sure	Some	No	Recorded in NRI	Management operations recorded (tillage etc.).	Cropland sites: selected based on tillage practice (NT and CT)	width of no-till opener recorded	conventional tillage