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# Current status, uncertainty and future needs in soil organic carbon monitoring ☆

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## HIGHLIGHTS

- Reliable data on global soil resources for the sustainable development are required.
- Information on the soil carbon pool, and its dynamics is unbalanced.
- Harmonized protocols for soil surveys and lab procedures are required.
- Long-term ecological research sites are backbones for soil carbon monitoring.

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## ABSTRACT

Increasing human demands on soil-derived ecosystem services requires reliable data on global soil resources for sustainable development. The soil organic carbon (SOC) pool is a key indicator of soil quality as it affects essential biological, chemical and physical soil functions such as nutrient cycling, pesticide and water retention, and soil structure maintenance. However, information on the SOC pool, and its temporal and spatial dynamics is unbalanced. Even in well-studied regions with a pronounced interest in environmental issues information on soil carbon (C) is inconsistent. Several activities for the compilation of global soil C data are under way. However, different approaches for soil sampling and chemical analyses make even regional comparisons highly uncertain. Often, the procedures used so far have not allowed the reliable estimation of the total SOC pool, partly because the available knowledge is focused on not clearly defined upper soil horizons and the contribution of subsoil to SOC stocks has been less considered. Even more difficult is quantifying SOC pool changes over time. SOC consists of variable amounts of labile and recalcitrant molecules of plant, and microbial and animal origin that are often

☆ Approximately thirty scientists from Europe, South America and the USA were involved in discussions regarding the future needs in soil C monitoring in a workshop of the Global Soil Carbon Network [G-SCAN], held in Florence, Italy, in April 2011. The workshop was hosted by Franco Miglietta. It was organized into three working groups, each dealing with different aspects of soil carbon monitoring: (1) Methodological standardization in order to compare existing studies and data sets and collect comparable data in the future; (2) Detection of changes in soil C pools (one of the major requirements to understand if a soil is a sink or a source of carbon); and (3) Long term experiments (used to disentangle the problems related to the long turnover times of soil organic matter). The current paper presents the major issues raised during discussions held at this meeting.

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operationally defined. A comprehensively active soil expert community needs to agree on protocols of soil surveying and lab procedures towards reliable SOC pool estimates. Already established long-term ecological research sites, where SOC changes are quantified and the underlying mechanisms are investigated, are potentially the backbones for regional, national, and international SOC monitoring programs.


## 1. Introduction

The amount of C stored in soils worldwide is estimated to add up to more than 3000 Pg (1 Pg = $10^{15}$ g, Jansson et al. (2010)). Soils not only contain C but also can represent a significant sink for atmospheric carbon dioxide ($CO_2$). Evidence for rapidly changing SOC pools has been shown for different ecosystems and continued warming may lead to strong climate-induced SOC loss (Bellamy et al., 2005; Cox et al., 2000; Rumpel and Chabbi, 2010; Post and Kwon, 2000; West et al., 2004). The effect of land-use change on the soil C pool was shown for an example of afforestation of marginal agricultural land with loblolly pine (*Pinus taeda* L.) plantations (Richter and Markewitz, 2001; Markewitz et al., 2002). Short-term soil C change data are increasingly available based on results from repeated national forest soil inventories in Europe (Jandl et al., 2012; Olsson et al., 2009). Activities for mitigation of climate change include soil-preserving management practices (Ogle et al., 2005; Powlson et al., 2011). Several policy initiatives such as the European Soil Thematic Strategy therefore put the preservation of the SOC pool prominently on their agenda in order to assure the sustainable and efficient use of the limited soil resource (European Commission, 2006, 2012). Methods, data needs, and models for the assessment of SOC changes at a spatial resolution relevant for decision making in land-use issues are not yet sufficiently elaborated (Smith et al., 2012). Global soil monitoring programs are still immature although the key role of SOC for human well-being has long been recognized (Lal, 2004). For a global soil C monitoring program representing the main types of ecosystems and allowing both the SOC stocks and the stock changes to be estimated, several challenges remain to be solved:

- The information on SOC is geographically unbalanced. An immediate challenge is the harmonization of already existing regional soil monitoring programs and soil databases.
- The identification of a universal metric for SOC monitoring is needed. Typically, information is available for the total C concentration, which is then converted to the total SOC pool. For a valid estimation of the SOC pool, the measurement of the soil bulk density and the content of rock fragments are equally important.
- A standardized approach to the reported soil depth for SOC pool estimations is required. SOC can be unevenly distributed over varying soil depths. Existing soil C maps are often based on data that poorly reflect the C pool of deeper soil horizons. The effect of land use changes on deep C stocks has been poorly addressed.
- The understanding of SOC stabilization processes is incomplete. No general agreement on soil C fractionation methods to estimate the degree of stabilization has been achieved.
- Specific field work protocols for the assessment of SOC dynamics are needed. The large spatial heterogeneity of SOC in comparison to its moderate temporal change calls for cost-effective sampling protocols in order to properly capture SOC dynamics on a landscape scale and to identify small SOC changes in a highly variable pool.
- SOC monitoring programs need to liaise with long-term soil experiment (LTSE). LTSEs offer a baseline for the SOC pool and can comprise a set of sites where targeted research on soil processes and their impacts on soil C can be performed. They can serve as a backbone for SOC monitoring.
- Mechanistic SOC simulation models are expected to play an important role in monitoring programs. They can assist in the estimation of temporal trends in the SOC pool, but they are not yet adequate for the extrapolation of existing soil information over space and time.

In this paper we describe the current status and the recognized obstacles for setting up a global SOC monitoring network. We analyze the options of soil C assessments and evaluate the different approaches with respect to their potential of assessing SOC pools and changes.

## 2. Present status of soil monitoring protocols

Current knowledge on the global distribution of soils and their properties is based on harmonized databases. The data are collected and databases are maintained by different stakeholders. Different efforts for mapping global soil resources are under way. Representative soil surveys are the basis for soil maps that ideally allow estimates of the total SOC pool to be derived (Table 1, van Wesemael et al. (2011)). In order to obtain an estimate on SOC pool changes, temporal trends need to be assessed by repeated soil inventories, or soil monitoring programs. Ground truth data from soil surveys provide an estimate of SOC

**Table 1**
Examples for existing and emerging large-scale soil assessment projects, including soil maps, soil C maps, and databases on soil C pools.

| Network | Region | Reported C | Ref. |
|---|---|---|---|
| FAO soil map | Global | Derived from soil profile data and pedotransfer rules | a |
| Global soil map | Global | Different mapping methods based on existing data | b |
| International Soil Carbon Network (ISCN), National Resource Inventory (NRI), Forest Inventory and Analysis (FIA) Program | U.S.A. | Based on measured SOC data from different data providers | c |
| National Ecological Observatory Network (NEON) | U.S.A. | Based on measured SOC data from different data providers | d |
| European Soil and Database (ESDB) map and Land Use/Cover Statistical Area frame Survey (LUCAS) | Europe | Based on harmonized data; topsoil SOC | e |
| Soil map Africa (AfSIS) | Africa | Based on heterogeneous data; in preparation by JRC | f |
| National Soil Database New Zealand (NSD) | New Zealand | SOC content in topsoil of agricultural sites | g |

[a] FAO/IIASA/ISRIC/ISS-CAS/JRC, (2008), http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116, accessed Aug 7, 2013.
[b] Project of the International Union of Soil Societies, http://www.globalsoilmap.net/, accessed Aug 7, 2013.
[c] http://www.fluxdata.org/nscn/SitePages/Home.aspx; accessed Aug 7, 2013, Nusser and Goebel (1997); http://www.fia.fs.fed.us/; accessed Aug 7, 2013; O'Neill et al. (2005); Spencer et al. (2011).
[d] http://neoninc.org; accessed Aug 7, 2013, under construction.
[e] Jones et al. (2004); European Commission (2005), http://eusoils.jrc.ec.europa.eu/library/esdac/index.html; accessed Aug 7, 2013, European 'Land Use/Cover Statistical Area frame Survey' (LUCAS) project.
[f] http://eusoils.jrc.ec.europa.eu/library/maps/africa_atlas/index.html; accessed Aug 7, 2013.
[g] van Wesemael et al. (2011); http://www.mfe.govt.nz/issues/climate/lucas/; accessed Aug 7, 2013.

pool changes and are also invaluable for the validation of SOC modeling results.

An example of an institutionalized assessment of soil resources is given by the activities of the European Community. The Joint Research Centre (JRC) holds the European Soil Data Center (ESDAC) and maintains the standardized European Soil Database (ESDB). ESDAC supports EU policies related to soil and land use, largely by providing key data sources to various stakeholders (Jones et al., 2005; Panagos et al., 2012). The "Land Use/Cover Area Survey" (LUCAS) project (Table 1) monitors landscape diversity, land cover, land-use changes, and soil chemical data, mainly on agricultural land. In the context of the development of ESDAC, the European Environment Information and Observation NETwork (EIONET) has been established with the aim of providing timely and quality-assured data and expertise to assess the state of the environment in Europe, and the pressures acting upon it. The JRC, through EIONET, performed a data collection exercise in 2010 among its member states with the final objective of creating a European wide data set for SOC and soil erosion according to a grid based approach. Originating from different data sources, the collected data have been harmonized to account for different methods of soil analyses, scales and time periods (Panagos et al., 2013).

Although several national programs exist (Table 1), there is a lack of global geo-referenced, measured and harmonized data on soil properties and specifically on SOC both available and reliable from systematic sampling programs. At the present time, homogeneous and comprehensive data on the SOC content are those that can be extracted from the ESDB and the National Soil Carbon Network (Table 1).

## 3. Sampling design, data evaluation and simulation models for the detection of soil carbon changes

### *3.1. Sampling design*

A well-known challenge of soil monitoring programs is how to account for the small-scale variability of soil properties such as rock fragment content, bulk density, and C concentration. In order to estimate the SOC pool with an acceptable level of accuracy, a large number of replicates are often necessary (Conen et al., 2003; Conant et al., 2011; Rodeghiero et al., 2009).

Different opinions are expressed concerning the appropriate soil sampling depth. In protocols aimed at shallow depths the field work is less time-consuming. A shallow sampling depth is often chosen for reasons of efficiency, as SOC predominantly accumulates at the surface and in the main rooting zone. By far, most soils are sampled to a depth of 0.3 m or less, and samplings below 1 m are an exception (Fig. 1). The recommended sampling depth varies between soil types and biomes. It has been shown that the SOC pool in the upper mineral soil is not a useful estimator of the total soil C pool as a substantial fraction of this pool can be stored in the subsoil. This has been shown for Mediterranean, temperate, boreal, and arctic ecosystems (Chabbi et al., 2009; Chiti et al., 2012; Harrison et al., 2011; Sletten and Hagedorn, 2012; Zabowski et al., 2011). Although the SOC pool in the subsoil is less dynamic over time it may contribute to changes in the total soil C pool (Lorenz et al., 2011). However, there are large differences in subsoil C among soil types (Fig. 1), and assessing the C content in deeper parts of the mineral soil may or may not be necessary. In a Spodosol on sandy and acidic bedrock (Fig. 1b), the depth distribution of SOC is shallow and subsoil sampling for the assessment of the SOC pool may be confined to the upper 0.3 m of the soil profile. On the contrary, in a Vertisol soil sampling only the upper horizons would greatly underestimate the total SOC pool (Fig. 1c). The issue of upper soil profile sampling is critical for upland soils. Wetlands require a different approach because their depth varies widely. For Finnish agricultural soils on drained wetlands an average depth of 1.1 m was assumed (Laine et al., 2004; Turunen, 2008). Tropical wetland soils may be as deep as 25 m (Rydin and Jeglun, 2006).

Some of the controversy regarding the appropriate sampling depth arises from the objective of the soil monitoring program. The sampling protocol may be different when C pools or C pool changes are to be quantified. In cases where the entire SOC pool is to be measured, even subsoil horizons must be sampled. Given that the primary source of SOC is derived from roots and soil microorganisms, and that the rooting depth of trees can reach up to several meters, a systematic underestimation of the SOC pool in forest ecosystems is possible (Stone and Kalisz, 1991; Rasse et al., 2005). This bias and the inconsistency of available databases for the total SOC pool introduce large uncertainties to global SOC pool estimates (Lorenz and Lal, 2010; Pan et al., 2011). In cases where changes in the SOC pool over time are relevant, sampling the upper mineral soil may be sufficient, because it holds the majority of metabolically active soil microorganisms. The SOC pool in the subsoil is often rather inert and has therefore a lower turnover time, although it contains recent and old C in close proximity (Chabbi et al., 2009; Trumbore, 2009). However, more data on temporal variability of subsoil SOC are needed before any generalizations can be made.

Additional challenges exist in forest ecosystems. A soil sampling campaign often avoids points of accumulated coarse woody debris, and biomass inventories often focus on standing biomass. The potentially

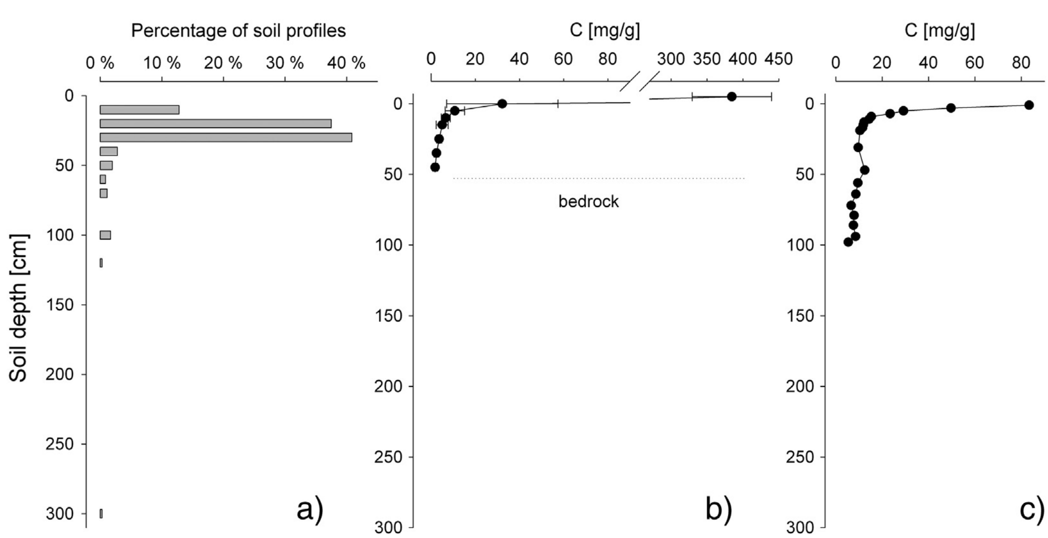


**Fig. 1.** (a) Sampling depths in a compilation of published soil profiles (Post and Kwon, 2000; West et al., 2004), and distribution of SOC in (b) a Spodosol soil of a pine (*Pinus silvestris*) forest in Altmanns/Upper Austria, and (c) a rangeland Vertisol from Stanley catchment, Hunter Valley, New South Wales, Australia (Martinez et al., 2010).

**Fig. 2.** Potential biases in the quantification of soil C pools due to preferential soil sampling: Plots with a local accumulation of coarse woody debris and soil pits with a high density of decaying coarse roots are avoided in field campaigns. Left picture: thinning residues in a young spruce forest in the Vienna woods (courtesy: Rainer Reiter), right picture: a high content of coarse roots in the soil samples collected by an auger profile.

substantial amount of necromass on the ground may be unaccounted for. In addition, soil cores are usually not taken at points where decaying tree stumps are abundant. Soil cores containing a large proportion of decaying coarse roots are often judged as being unrepresentative and are discarded. Thus, in natural forests the SOC pool may be systematically under — rather than overestimated (Fig. 2).

In order to make the best use of soil surveys, a sample archive is useful. More than 100 archives exist and many have been established within the past 60 years (Richter et al., 2007; Richter and Yaalon, 2012). The archives are often based on a personal initiative and are not necessarily part of a long-term strategy. Several success stories of the re-assessment of archived soil samples have been made. The stability of the SOC pool over several decades was demonstrated by the comparison of C contents from recently collected samples with reanalyzed samples (Torn et al., 2002).

### 3.2. Soil carbon simulation models

Monitoring and predicting changes in the SOC pool can be challenging given the slow rate at which changes occur. The full impact of management changes, for example, can often take decades to become apparent, thus a long-term monitoring approach coupled to a modeling approach is required.

Soil C models of different complexity are available (Coleman and Jenkinson, 2008; Easter et al., 2007; Gärdenäs et al., 2011; Liski et al., 2009; Parton et al., 1994). Some require a large amount of input data whereas others can be parameterized with commonly available site data. Rather complex models perform very well for highly-instrumented research sites and may be used for the development of ecological theory. In order to comply with the reporting requirements for national greenhouse gas budgets and in order to simulate the SOC dynamics of a large area the user often has to stick to rather simple models.

Two types of models can be used to simulate changes in SOC stocks at the regional scale: (i) macro scale models that are designed at a coarse scale and use simplistic equations, and (ii) ecosystem models that are designed at the plot or farm scale and use complex functions generally routing the soil C through a number of pools with different residence times (Paustian et al., 1997). These ecosystem models can be run for polygons with a specific combination of soil, land use and climate characteristics (Falloon et al., 1998). An example is the estimation of the regional SOC changes in central Hungary (Coleman and Jenkinson, 2008). Such an approach is, to date, limited to SOC stocks in the topsoil, usually the plough layer.

While SOC dynamic models have been extensively validated on long term experiments (Smith et al., 1997b, SOMNET), collecting a comprehensive data to allow for validation at the regional or national scale remains a challenge. For Belgium, around 600 soil profiles of an extensive historic soil inventory from the 1960's were re-sampled in 2005 covering the major soil types and agricultural regions and the change in SOC stock was assessed. The RothC model simulated the changes in SOC stock for 23 combinations of agricultural regions and soil types in both grassland and cropland (Meersmans et al., 2010; van Wesemael et al., 2010). The largest decreases in SOC stocks (11 to more than 45 Mg ha$^{-1}$) occurred in poorly drained grassland soils as a result of improved drainage upon land consolidation since 1960. Large increases in well-drained grasslands (12 Mg ha$^{-1}$) could be explained by historical conversion of cropland soils. Apart from the areas where intensive livestock breeding became the dominant land use, cropland soils generally lost around 14 Mg ha$^{-1}$ over the fifty year period.

Information on long-term management is crucial in order to explain these regional patterns in SOC changes. Unfortunately, detailed management data are rarely consistently recorded over long periods. The National Resource Inventory (NRI, see Table 1) is an exception. From 1979 data were recorded for ≈800,000 sites and the Century model was used to assess changes in the U.S. national SOC stocks including an uncertainty analysis (Parton et al., 1994; van Wesemael et al., 2011). The model was run for the NRI sites, and upscaled to national stocks using expansion factors. An alternative approach was the use of an empirically-based estimator to compare SOC stocks predicted by Century with observed SOC stocks in more than 800 treatments of 47 long-term experiments (Ogle et al., 2007). Their linear mixed-effect model indicated that Century had a tendency to under-estimate the SOC stocks in treatments with organic amendments or with grass leys in the rotation. Similar spatially explicit model approaches to assess changes in SOC stocks have been developed in projects for national greenhouse-gas inventories (Easter et al., 2007). It is expected that observed SOC changes from soil monitoring programs will become available and will be used to quantify the uncertainty associated with these estimates.

While model predictions of the future cannot be verified using measured data, it is possible to obtain insights into the model performance by assessing their ability to simulate long-term C dynamics using existing long-term data sets (Smith et al., 1997b; Palosuo et al., 2012). Long-term ecological research (LTER) sites that have reached equilibrium are ideally suited for model calibrations, and a comparison of model performances has been published (Smith et al., 1997a). However, the fact that LTER experiments are rarely replicated may limit the confidence in SOC model predictions.

### 3.3. Chronosequences

“Space-for-time” substitutions can overcome the disparity between the long time-scale over which ecological dynamics occur, and the typical short duration of conventional experiments or observations. Chronosequences are located on sites with identical conditions, but of different age. Under the assumption that sufficiently similar sites can be found, chronosequences allow the effect of time on selected properties to be investigated (Fukami and Wardle, 2005). Thus, it may be possible to study the effects that may take decades to be detectable. Space-for-time substitutions have several advantages: (1) they are more cost-effective and easier to establish and implement than long-term studies, (2) they examine processes and mechanisms directly, (3) they provide insights into processes occurring at long time scales during the course of a short-term study, and (4) they can be established in parallel to long-term studies, to increase the time scale over which dynamics can be explored and verify the results achieved at long-term sites. Despite their intriguing simplicity chronosequences are often difficult to implement effectively in practical research. Known problems include the challenge of locating sufficiently similar sites. In addition, even when differences in soil properties on otherwise similar sites are encountered it may be questionable to assign differences exclusively to temporal effects (Yanai et al., 2000).

For example, the C pool of Austrian forest soils was investigated using a space-for-time substitution. The underlying hypothesis of the comparison was that spruce forests have a lower soil C pool than forests of deciduous trees when subsoil horizons are included in the survey. Chronosequences of 5 to 100 year old spruce (*Picea abies*), beech (*Fagus sylvatica*), and oak (*Quercus petraea*) forests were compared. A thick litter layer typically forms under immature spruce because its needles decompose slowly. However, spruce is known to develop a shallow rooting system so that the soil C input to the subsoil due to decaying roots is rather small. The hypothesis was only partially confirmed. The soil C pool was rather similar in the mineral soil, but the depth distribution was different. The beech and oak forests had higher SOC pools in the subsoil whereas spruce forests had most of their SOC in the upper mineral soil (Veselinovic and Hager, 2012, 2013).

### *3.4. Laboratory methods of C in soil and soil organic matter fractions*

Carbon is present in soils in an organic and inorganic form. In calcareous soils with neutral to basic pH, inorganic C can make up a significant fraction of the total C, whereas in acidic soils it is absent. The chemical quantification of total soil C is performed by dry combustion in an Elemental Analyzer (EA), while inorganic C is commonly measured by the pressure transducer method where the $CO_2$ pressure builds up after addition of HCl (Sherrod et al., 2002). Organic C can then be obtained by difference. Also, organic C can be measured by EA, after acid digestion of the samples (Harris et al., 2000), but a correction factor may be needed at high concentrations of inorganic C (Ramnarine et al., 2011). A few laboratories, where an EA is not available, use wet chemical oxidation of organic C, referred to as the Walkley-Black method (Walkley and Black, 1934) to determine SOC. Conversion equations for the harmonization of C data have been derived but need to be used with caution because the readily oxidizable C measured by the Walkley-Black method is not necessarily correlated to the measurement by EA (Gerzabek et al., 2005; Conyers et al., 2011).

Soil organic matter (SOM) is a heterogeneous matrix with respect to its chemical structure and physical protection and consists of many compounds of different decomposability and turnover times (Schmidt et al., 2011). In recognition of this heterogeneity several operationally defined fractionation schemes have been proposed (Denef et al., 2009; Crow et al., 2007; von Lützow et al., 2007). The physical fractionation by size and density has proved to be biologically meaningful (Grandy and Neff, 2008), since it isolates fractions from plant debris (e.g. light fraction, $\rho < 1.8$ g cm$^{-3}$) to the microbially processed and minerally stabilized organic matter (e.g. silt (53–2 μm) and clay (<2 μm) associated fractions). The method is capable of separating fractions in terms of stabilization mechanisms and turnover times (Stevenson and Elliott, 1989). Wet sieving can also be used to quantify the state of aggregation of SOM, and thus its state of physical protection from decomposition (Six et al., 2002).

In studies of SOC changes, the physical fractionation of SOM allows the C pool to be broken up into its various smaller compartments and therefore it increases our power to determine SOC changes. Also, by identification the fraction subject to change can improve the interpretation of the long-term changes (del Galdo et al., 2003). Even when no changes are detected at the level of the bulk soil, a shift in the SOC allocation among the fractions may indicate a significant change in SOC stocks in the long-term. Climate change altering plant productivity and microbial decomposition rates can alter the SOC allocation among its primary components. Therefore, in climate change studies the use of physical fractionation separating the light and heavy fraction and the silt fraction from clay-stabilized SOM is recommended (Marzaioli et al., 2010). Land use and management alter the aggregation, and thus in these studies the quantification of SOM macro- and micro-aggregates is encouraged (del Galdo et al., 2003; Six et al., 2002).

Physical SOM fractionation schemes are generally tedious and time consuming. Over the last few years, mid-infrared-spectroscopy has been explored as an alternative to demanding lab fractionation protocols. The spectra are distinguished between labile and recalcitrant fractions of SOM (Cécillon et al., 2009; Foley et al., 1998; Leifeld and Kögel-Knabner, 2005; Zimmermann et al., 2007). The disadvantage is the need for calibration with a large set of samples.

## 4. Long-term soil experiments

LTSEs are defined as field experiments with permanent plots that are periodically sampled to quantify soil change across decadal time scales. They provide invaluable information regarding soil change and functioning, as well as biological, biogeochemical and environmental sustainability. Understanding the past and present ecosystem dynamics may be key to properly predicting future conditions, even though global change creates site conditions that may or may not have precedents. Much of our present knowledge regarding soils and sustainable land use is based on the results from LTSEs, both from forest and agricultural experiments (Rasmussen et al., 1998; Körschens, 2006; Richter et al., 2007).

The maintenance of monitoring programs is often difficult to reconcile with the time frame of research funding schemes, and LTSEs are rarely represented in top-down research programs. Monitoring experiments started in Europe within the agricultural sector with an emphasis on crop productivity. The classical Rothamsted experiment was initiated in 1843 and is still in progress. Forest ecosystem monitoring has initially been pursued in the context of forest hydrology. Under the impression of devastating floods a comparison of the hydrology of the fully forest-covered Sperbelgraben and the less forested Rappengraben in Switzerland was started. The experiment is still active (Hegg et al., 2006). In the 20th century many long-term experiments were established. At forested sites the focus was on hydrology, forest nutrient and nutrient cycling, and later on soil acidification (Ågren and Andersson, 2012; Ellenberg et al., 1986; Johnson and Lindberg, 1992; Richter and Markewitz, 2001, Fig. 3). The "International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests" (ICP Forests; http://www.icp-forests.net/; accessed Aug 6, 2013) was coordinated by the European Community in 1986 and later the European Union, and is now operating under the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution. Within its Level I and Level II programs the monitoring in European forests was centralized. In retrospect, many long-term experiments have proven to be valuable for the interpretation of temporal ecosystem dynamics. As a reference for the C sequestration potential of forest soil baselines of soil C pools have been derived from LTER data (Lark et al., 2006; Baritz et al., 2010). Within the"BioSoil Demonstration project" a fraction of the Level I inventory of 1995 was resampled between 2006 and 2008. The aim of the project was to demonstrate, under the Forest Focus Regulation, that a large scale European exercise can provide policy support on the basis of harmonized data. A comparison between the data collected on C in the

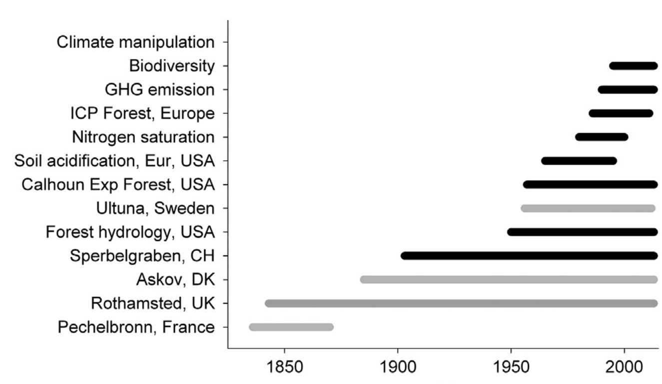


**Fig. 3.** Examples for the record of long-term ecological research in agriculture (gray) and forestry (black).

**Table 2**
Soil sampling effort level: the levels are in order of effort required, from lower (level 1) to higher (level 4).

| | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|
| | Field work | | | |
| Monitoring description | No statistical design | Random sampling | Stratified random sampling | Nested sampling design |
| Samples per plot | 1 | 3 | 3 | >3 |
| Sampling device | Gauge auger | Edelman auger | Undisturbed core | Pit excavation |
| Depth | Forest floor and topsoil | Forest floor + 30 cm mineral soil | | Forest floor + mineral soil to bedrock |
| Layers | No distinction | Two layers of equal thickness | Four layers (0–5, 5–10, 10–20, 20–30 cm) | Four layers + pedological classification |
| Bulk density | No estimation | From general pedotransfer function | From site-calibrated pedotransfer function | Measurement |
| Stoniness | No estimation | Standard coefficient | Visual estimation | Volume measurement |
| Roots | No estimation | Standard coefficient | Biomass equations | Volume measurement |
| Superficial obstacles | No estimation | Rough estimation of area covered by boulders | Measurement of area covered by boulders | Measurement of area covered by boulders and stumps |
| | Lab analysis | | | |
| Pooling | Bulk sample | | Individual sample | |
| Carbon content | Walkley-Black | | Dry combustion | |
| Fractionation | None | By size | By density | By size and density |
| IR spectroscopy | No analysis | | IR analysis | |
| Texture | No texture | | Texture analysis | |

initial survey and the BioSoil data demonstrated many of the difficulties associated with carrying out a harmonized SOC monitoring exercise for European forests (Hiederer et al., 2011; Rantakari et al., 2012).

A potential problem of LTER data is that SOC measurements are rarely replicated. Without an assessment of the uncertainty the use of the data is seriously limited (Falloon and Smith, 2003). Another challenge is the recognition of the unusual change in data sets with an otherwise noisy time trend (Barnosky et al., 2012).

Selecting sites for LTSEs is a challenging task. Selection according to soil types is a feasible solution because soils integrate a variety of factors, and soil properties are often used to guide choices in land use and management by local farmers and management authorities. LTSEs are important for monitoring not only SOC but also ecosystem processes. While soil is a large and important resource, and the SOC pool is a significant sink for atmospheric $CO_2$, they form part of, and are fundamentally connected to the environment (i.e. biosphere, atmosphere and hydrosphere). Thus a whole-system approach provides the best method by which to investigate global soil change at a range of scales, such that soil changes can be related to larger ecosystem responses and a broader range of environmental conditions (Rustad, 2008).

The European Soil Organic Matter Network (EUROSOMNET) includes over 110 LTSEs located throughout Europe and parts of the former Soviet Union (Franko et al., 2002). More recently, a global network of LTSEs was launched with the aim of expanding observations of global soil change by coordinating and promoting data collected at existing LTSEs globally (http://www.nicholas.duke.edu/ltse/; accessed Aug 7, 2013). Currently, over 250 soil experiments participate in this online resource. Most sites are in the temperate zone, and a large proportion represents agricultural land in developed regions. The representation of soil types is unbalanced and chemical analyses are confined to the upper mineral soil horizons (median depth = 15 cm; for ≈90% of samples the depth is below 30 cm). There is a need for the number of LTSEs to expand and diversify, to have a representative network of all the major ecosystems, soil types, land use and management systems, and soil depths globally. However, it may be just as important to ensure that existing long-term experimental sites are maintained and supported, given that the value of long-term experiments increases with age (Richter et al., 2007; Richter and Yaalon, 2012).

Another information resource is the Geographical Network of Field Experiments. It was founded in Russia in 1941 and currently includes over 300 experiments, with approximately 40 sites over 40 years old. Most of them are located in the Ukraine, Belarus, Moldova, and Georgia (Shevtsova et al., 2003). These sites, however, are largely unknown outside of Russia.

In order to maximize the effectiveness of data generated from LTSEs an option is to integrate them with gradient studies. Observations across a range of gradients such as latitude, longitude, elevation, climate, pollution, or species, provide opportunities to explore global change issues and various factors using an integrated approach. Superimposing experiments across gradients enables scientists to adopt a whole ecosystem approach and investigate ecosystem responses to a broader range of environmental conditions (Rustad, 2008).

## 5. A concept for soil sampling

There are many techniques and methodologies available for soil sampling and analysis (Rodeghiero et al., 2009). A Soil-Sampling-Effort-Level (SEL) classification may be needed, and organized into a table according to the level of effort required to collect the data to estimate the C content per unit of surface area (Table 2). Soil sampling is time-consuming. Whereas in agricultural soils undisturbed cores can be collected with augers, while in forest ecosystems, due to the presence of variable quantities of stones and coarse roots, it is often necessary to excavate samples. The heterogeneity of forested sites also makes the identification of a suitable location for sample collection for bulk density challenging (Page-Dumroese et al., 1999). Soils are probably too heterogeneous, being a mix of organic and inorganic particles (minerals, stones, roots, organic residues, water, micro-organisms, fungi etc.), to use any kind of sensor to detect different soil constituents. The most difficult to determine and spatially variable constituent is probably soil stoniness. However, large errors can result if this component is not adequately accounted for (Rodeghiero et al., 2009, 2011).

Table 2 gives an overview on existing methods that are presently encountered in SOC assessments. Whereas all of them are suitable to obtain estimates of the SOC pool, only elements of the highest effort levels allow conclusions regarding SOC pool change over time to be derived. Of particular importance is the relevance of field work. A thorough assessment of soil volume and soil bulk density is equally as important as accurate measurements of the C concentration of the bulk soil or even SOM fractions.

## 6. Conclusions

Currently, several efforts aimed at creating global soil C maps are underway. Conceptually, the approaches are different, as the SOC pool can be derived from soil morphological properties, or from measured SOC concentrations. The first approach is based on a higher density of data. Since the primary intention is the creation of a global soil map, the derived soil C map can be seen as a secondary product. Because the displayed SOC stock is already an approximation, such maps are unsuitable for the assessment of SOC changes. However, they can – together with other elements of information – yield relevant information on potential hot-spots for SOC changes.

The second approach can yield more accurate SOC pool maps, if additional parameters, such as soil bulk density and rock content are available in a similar level of quality. In cases where the uncertainty of the SOC pool estimate is available, the assessment of SOC changes is possible.

Ideally, efforts between the soil mapping communities are joined. It takes a committed community of soil experts that is furnished with the required infrastructure and funding to accomplish the goal. Unlike in many other fields, earth observation systems are so far not offering a remedy. The required data are collected in programs where field work is having a major role. In recognition of these challenges the efforts of creating soil C maps are far from being completed. There are still strong discrepancies in the regional coverage of SOC information and combining information from regions with a high density of measured data with almost uncharted regions is a challenge. An important advantage of the maps already presented is to highlight which regions the most relevant information gaps exist.

A global SOC monitoring program needs to be driven by a clearly formulated need. A pre-requisite is the identification of regions where SOC changes are most likely, and of regions where the expected changes have a relevant extent. Therefore, a logical starting point is to focus on regions that at present have high SOC stocks. The second step is the identification of the main processes leading to SOC changes. These may be regions with accentuated rates of land-use change, or regions that are expected to be most strongly affected by climate change.

Another topic is the focus on lab procedures. A global SOC monitoring program needs standardized lab protocols. Presently, many methods for the analysis of C concentrations of the bulk soil or its fractions are available and all have their undisputed merits. With hindsight on the decentralized data generation it is feasible to suggest ISO-standardized methods for the measurement of the C concentration and to document them in a manual.

In a similar fashion modeling efforts need to be evaluated. Whereas the development of sophisticated models is well justified for the application in a regional context, the global soil C monitoring needs to rely – for the time being – on simulation models that can be parameterized with standardized input data that are globally available. All modeling exercises need to be validated with ground truth data. The existing LTSEs can have a decisive role for the quantification of the effect of soil processes leading to SOC changes, and for the validation of modeling results. In the last years significant progress has been made in assessing global SOC pools and in assembling comprehensive SOC databases. However, in order to meet the information needs of the 21st century, an internationally organized and globally acting SOC network such as the International Soil Carbon Network (Table 1) will be required.

Besides its scientific challenges the establishment of a global SOC network is demanding with respect to the secondment of infrastructure and manpower. It requires a strong commitment by leading soil science institutions and the readiness for joining forces and overcoming institutional barriers. Establishing a global soil monitoring network will be a long and tedious process with many highs and lows. It will require the endurance of the involved scientists, and continuous funding in order to scrutinize and integrate emerging information in the already existing systems. The expected benefit of a functional global SOC information system will be tremendous, equally for policy makers, land managers, and the scientific community.

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