Project no. 212196
COCOS

Workshop on mapping of soil carbon stocks at the global scale

Martin Köchy*, Annette Freibauer

vTI-AK, Bundesallee 50, 38116 Braunschweig, Germany
*martin.koechy@vti.bund.de

Deliverable type: Report
File name: D1.4 SoilMappingWorkshop.pdf
Deliverable reference num.: D 1.4

Instrument:	Coordination and support action
Thematic Priority:	Earth Observation and assessment tools for sustainable development
Due date of deliverable:	month 30
Submission date:	20 July 2011
Start date of project:	1 May 2008
Duration:	36 months
Deliverable lead contractor:	vTI
Revision:	1.1, 2011-07-25, 2011-08-08
Work Package:	WP 4
Document ref number:	D1.4

Workshop Details	
Title	Workshop: Mapping of soil carbon stocks at the global scale. International workshop for advancing global carbon monitoring with respect to soil carbon mapping.
Date	15/16 July 2011
Location	Leuven, Belgium
Host institute	vTI Institute for Agricultural Climate Research
Registrations	14 from AU, DE, EU, IT, NL, UK, UN, US
Participants	13 + 2 hosts

List of participants

Mirco RODEGHIERO	E. Mach Foundation	Current status, uncertainty and future needs in soil carbon monitoring
Ronald VARGAS	FAO	Towards a Global Soil Partnership for food security and climate change adaptation and mitigation
Roland HIEDERER	JRC	Mapping and Monitoring Soil Organic Carbon
Barry RAWLINS	Brit. Geol. Survey	Covariates and approaches for mapping soil carbon concentrations across carbon-rich terrains
David GREENBERG	U Oxford	Geostatistical mapping of Amazon forest soil carbon stocks
Gabriele BROLL	U Osnabrück	Northern Circumpolar Soil Carbon Database
Thorsten BEHRENS	U Tübingen	Digital soil organic C mapping at field to global scales
Nathan ODGERS	West Virginia U/NRCS	Application of the equal-area spline function to legacy soil data
Pat BELLAMY	Cranfield U	Mapping changes in soil organic carbon at a national level
Günther SPRINGOB		Mapping of soil carbon at the global scale
Martin KÖCHY	vTI	Vulnerability of global carbon stocks
Martin KNOTTERS	ALTERRA	Sampling for mapping and monitoring of soil carbon stocks
Eddie LOONSTRA	The Soil Company	Proximal gamma-ray soil sensors: potential role in mapping C stocks
Jeff BALDOCK	CSIRO	Modelling the spatial stocks and composition of soil organic carbon
Annette FREIBAUER	vTI	

Introduction

Soil carbon stocks are dependent on multiple factors that act at multiple spatial and temporal scales. Inorganic carbon compounds in the soil are usually the result of the weathering of carbonate bedrock. Organic carbon enters the soil mainly in the form of plant residues (litter): shed leaves or dead roots or burned plant material. The chemically complex organic matter is decomposed by animals, fungi, and bacteria to CO_2, which enters the atmosphere, or less complex organic substances, which can accumulate in the soil. The amount of organic carbon in the soil is a dynamic equilibrium between carbon input and its decomposition whose rates are controlled by litter quality, temperature, soil moisture, oxygen availability and soil reaction. Decomposition rates vary between hours and centuries, depending on conditions and the carbon compounds.

The global soil organic carbon stock is greater than the combined atmospheric stock and the stock contained in living biomass. Therefore, small changes in the soil carbon stock can have profound effects on the concentration of atmospheric CO_2 and hence climate change. Despite its importance, the amount and distribution of the current stock of soil carbon is not well known, especially for carbon below 1 m soil depth.

The spatial distribution of carbon stocks is commonly derived from soil maps, where areas with similar soil characteristics form so called soil mapping units, and integrating the soil carbon stock per area of soil mapping unit. Soil maps are based on the experience of soil surveyors taking into account topography, climate, land use history, vegetation, bedrock, and soil characteristics measured on representative vertical soil profiles. The scientific community, however, is moving away from using soil maps to producing continuous surfaces of soil properties such as carbon stocks using geostatistical techniques

The organic carbon stock of a soil is determined from measuring the carbon concentration (CC) and the density (ρ) of undisturbed soil samples in homogenous soil layers of thickness d. The stock is calculated as $CC \cdot \rho \cdot d$ (more exactly referred to as ‘areal density’). The amount is reduced for the volume occupied by gravel, rocks and roots in the soil layer. The calculations are integrated over all layers for the total organic carbon stock of the soil (or within a specified depth).

The workshop addressed uncertainties associated with sampling soils, measuring and calculating carbon stocks of samples, integrating over depth and areas, interpolating from points to areas, and combining information from different regions and times.

Abstracts

Current status, uncertainty and future needs in soil carbon monitoring

M. Rodeghiero

The need for cataloguing global soil carbon was recently highlighted by Gianelle *et al.*, (2010) in a letter to Science, where the importance of considering soils and SOM sensitivity to temperature were underscored. Moreover the need to understand the global distribution of soil carbon is a real concern for climate change international policy issues.

In order to establish the status of our knowledge regarding global soil carbon stocks in relation to climate change problems, an International workshop named G-SCAN (Global Soil Carbon Network) was organized in Florence (20-21, April) by the Edmund Mach Foundation (San Michele All'Adige, Italy). Some of the top scientists working on soil carbon dynamics from Europe and the US discussed the topic according to three working groups: a) Methodological standardization of soil C stocks; b) Detecting changes in Soil C; and c) Long-term experiments.

Starting from real situations of soil carbon inventories and databases, the main problems and needs related to monitoring were highlighted and discussed. The results of the workshop will be published soon as an opinion paper in a peer reviewed journal. The unresolved problems still concerning soil carbon monitoring were discussed and could serve as a basis to homogenize current databases, compare soil inventories and improve global soil mapping.

Towards a Global Soil Partnership for food security and climate change adaptation and mitigation

Ronald J. Vargas Rojas

Soils can be considered as non-renewable in the time frame of human activities. There is increasing degradation of soil resources due to population pressures, inappropriate practices and inadequate governance over this valuable resource.

The renewed recognition of the central role of soil resources for assuring food security and the increased awareness that soils play a fundamental role in climate change adaptation and mitigation has triggered numerous projects, initiatives and actions that need an increased effort of coordination and partnership in order to avoid un-necessary duplication of efforts and waste of resources, especially in times of substantial budget restrictions.

On the basis of the recommendation of FAO's High-Level External Committee (HLEC) on the Millennium Development Goals to the Director-General and the discussions and conclusions from the 22nd Committee on Agriculture (COAG), preparatory activities have been initiated to develop a vision statement, strategy and action plan towards the establishment of a Global Soil Partnership (GSP) for Food Security and Climate Change Adaptation and Mitigation.

The GSP will aim towards collaboration and sharing of responsibilities so as to provide a coherent framework for joint strategies and actions. The GSP should aim at facilitating the dialogue and interaction among the various users and stake-

stakeholders currently competing for the use of soil resources at global scale. This will complement similar initiatives for water (the Global Water Partnership) and land (Voluntary Guidelines on the Responsible Governance of Tenure of Land and Other Natural Resources (VG)).

The Global Soil Partnership's mission is to support and facilitate joint efforts towards sustainable management of soil resources for food security and climate change adaptation and mitigation.

In order to achieve the aforementioned objectives, it is proposed that the GSP should address five main pillars of action: a) Harmonization and establishment of guidelines and standards of methods, measurements and indicators; b) Strengthening of soil data and information: data collection, validation, reporting, monitoring and integration of data with other disciplines; c) Promoting targeted soil research and development focusing on identified gaps and priorities and synergies with related productive, environmental and social development actions; d) Promoting sustainable management of soil resources and improved global governance for soil protection and sustainable productivity, and e) Encouraging investment and technical cooperation in soils.

The sustainable and productive use of the soil resources of the world should therefore be the ultimate twinned goal of the GSP.

Mapping and monitoring soil organic carbon

Roland Hiederer

Within the last 20 years the demands for assessing organic carbon stocks have undergone significant changes from being a niche activity of recording the effect of managing practices on cultivated land to playing a prominent role as a potential mitigating factor to climate change. With the expansion of the thematic scope the geographic extent of the area of interest increased form following changes at field level to estimating SOC with regional and global coverage.

Maps on the distribution of soil organic carbon are often derived from general soil databases which are not specifically produced to cater for the demands of assessing and modelling organic carbon. Practical considerations of comparing a SOC map generated from the Harmonized World Soil Database with other global SOC map products are considered. When comparing global maps of OC the total SOC stocks remain within the range of the estimate given by IPCC, but at local level marked variations are present. They also indicate a rather indistinct association of OC with land cover and climatic condition in gridded data.

For a more in-depth assessment of the interaction of SOC with environmental conditions data from field surveys become indispensable. The evaluation of the BioSoil demonstration project is presented as an example of the benefits and limitations of a field survey with special focus on assessing SOC. The survey results highlight in particular the need for applying consistent measurement procedures and analysis methods to provide a meaningful evaluation of temporal changes in SOC stocks.

Covariates and approaches for mapping soil carbon concentrations across carbon-rich terrains

Barry Rawlins, Murray Lark, Monica Barker & various co-workers

We will address three topics related to uncertainty in SOC mapping and inventory:

i) differences in the dominant scales of SOC variation in topsoil and subsoil across agricultural landscapes, and the fixed effects which might be used to map SOC
ii) considerations of single core versus aggregate supports for soil sampling schemes
iii) why and where airborne radiometric survey data might be an effective covariate for mapping SOC concentrations

Across temperate (agriculturally dominated) terrains of the UK, parent material type and land use have significant predictive power as fixed effects in mapping SOC concentrations in topsoil (0 to 15 cm depth). Its variation at short scales (20 metres) is an order of magnitude smaller compared to medium scales (~1km). In the case of subsoil (35 to 50 cm depth), we observe the same relative magnitudes of the variance components; they decrease by an order of magnitude from coarse (>1km) to finer scales. However, in contrast to the topsoil analyses, the variance of the analytical plus subsampling error component in subsoil was larger than the short scale component. This may be attributable to the different analytical approaches. Loss-on-ignition was used to estimate SOC in the topsoil, whilst combustion with elemental analysis was used for the subsoil samples implying that -because sample preparation was consistent - the former analytical method is more precise. Only Soil Group was statistically significant ($P<0.05$) as a fixed effect for estimating subsoil carbon concentration; land use [at the time of sampling] was not significant.

Soil sampling schemes often use aggregate supports - material from a set of soil cores, arranged in a given configuration – which are aggregated and mixed before analysis. Spatial statistics of soil information, collected on an aggregate support, can be computed from the covariance function of the soil variable on a point support by a discrete regularization of the point support function. Discrete regularization can be used to compute the variance of soil sample means, and to quantify the consistency of soil monitoring given uncertainty in relocation of sample sites. Using data on SOC concentrations along a transect, it is shown that the precision and the consistency of data collected on an aggregate support are better than data on a core support which has implications for inventory and monitoring.

Airborne radiometric survey data (specifically the K channel) and topographic information substantially improve estimates of SOC concentration across the carbon-rich terrain of Northern Ireland (using a linear mixed model framework). More recent analyses have shown that using a form of disaggregation (Area-to-Point kriging) of polygons from legacy soil maps can further reduce errors associated with SOC estimation by independent cross validation. We discuss the circumstances in which airborne radiometric survey data is likely to be most effective as a covariate for mapping SOC at regional scales.

Can spatially-varying effects of environmental processes on soil carbon content help us make better maps?

David B. Greenberg

With decades of rising atmospheric CO_2 concentrations behind us, and with the rate at which those concentrations increase currently accelerating, advancing our efforts to map both the magnitude and vulnerability of global soil carbon stocks has become more important than ever. We tend to agree that using environmental co-variates as predictors during spatial interpolation, e.g., with such approaches as universal kriging, can be reasonably successful; however, these procedures normally assume something very unlikely — that the effects of physical and biotic processes on any given target variable are themselves stationary. The purpose of this talk is to illustrate non-stationarity in these effects, using geographically weighted regression of WISE and WorldClim data, revealing that the effect of temperature on topsoil carbon content varies widely across tropical America in which case simply using a distance-weighted regression on temperature to predict topsoil carbon content would be considerably less successful within large areas of the region than we might have anticipated. Further, whether or not temperature has even any effect whatsoever on topsoil carbon content varies widely across tropical America, meaning that in many areas traditional co-variate based spatial interpolation would be completely unsuccessful. With this talk I hope to stimulate discussion on how we can use such non-stationarity in the effects of environmental processes on soil carbon to advance our science.

Northern Circumpolar Soil Carbon Base

Gabriele Broll & Charles Tarnocai

About twenty years ago the Cryosol Working Group, associated with the International Permafrost Association (IPA) and the International Union of Soil Science (IUSS), started to develop the Northern and Mid-Latitude Soil Database including several common soil parameters. The soil area of the northern circumpolar permafrost region is about 18 million square kilometres, and Cryosols cover approximately 40% of this soil area. Because of the increasing relevance of carbon data the development of the Northern Circumpolar Soil Carbon Database (NCSCD) started about ten years ago. Since about five years the Carbon Pools in Permafrost Regions initiative (CAPP) under the auspices of the International Permafrost Association (IPA) is involved too.

The purpose of the NCSCD is to facilitate the estimation of the organic carbon pools in the northern hemisphere. The database contains approximately 80 thousand polygons, for which the percent distribution of the various soils and their properties are documented. The NCSCD can be used to calculate the organic carbon content and the organic carbon mass of each soil in each polygon. The total carbon masses for perennially frozen, seasonally frozen and unfrozen soils in the various regions can then be calculated using this information. In addition to determining the organic carbon stocks for the northern circumpolar region, the NCSCD will also be able to provide information for up-scaling terrestrial carbon, and for modeling the effect of climate change on soil carbon in the various permafrost and non-permafrost soils.

Soil data in the NCSCD are derived from soil data available for the various countries. The data require careful correlation because the data generated by the various countries are often obtained using different standards and methods. Special attention has been paid to organic soils, which are very sensitive to climate change and widespread in the northern area.

Digital soil organic C mapping at field to global scales

Thorsten Behrens, Raphael Viscarra Rossel, and Karsten Schmidt

The aim of this talk is to present the current state of research on the spatial analysis of soil organic carbon.

We present various case studies that show our current research on digital soil organic carbon (SOC) mapping at field, regional, continental and global scales.

Our methodologies comprise the use proximal soil sensors, innovative soil sampling and mapping strategies, but also the use of legacy soil data in a framework for digital soil mapping that is based on state-of-the-art spatial data mining techniques. Within this framework we also apply a new hyper-scale mapping approach (ConMap) that outperforms common digital terrain analysis as an important source for covariates for SOC mapping.

The datasets that we use originate from various sources. At the global scale, we use data from the new global soil spectral library (GSSL) with more than 16,000 spectra and soil organic carbon data form various depths.

We hope that our presentation will incite discussion on the success of the approaches and also on their limitations so that we may improving the approaches for digital SOC mapping.

Application of the equal-area spline function to legacy soil data

Nathan P. Odgers, Zamir Libohova, Alex. McBratney, James Thompson

Splines have often been used to approximate continuous depth functions of soil properties. The equal-area spline fits quadratic curves piecewise through soil horizons down the soil profile; these quadratic curves are joined at the soil horizon boundaries. The equal-area spline is so-called because the area between the mean property value and the portion of the curve above the mean value, and the portion of the curve below the mean value, respectively, is equivalent, which preserves the mean soil property value across the entire soil horizon as a whole. The splines are a rapid, effective way of estimating soil property values at user-specified standard depth increments, and do not require profiles to be sampled at fixed depths in order to do so.

We demonstrate the use of the equal-area spline function for mapping weighted means of organic carbon across the contiguous United States from the United States Department of Agriculture-Natural Resources Conservation Service's 1:250,000 STATSGO2 database at the standard depths prescribed by the GlobalSoilMap.net project. In addition, we outline one method of estimating uncertainty for the weighted means maps.

Mapping changes in soil organic carbon at a national level

Pat Bellamy

I will review recent developments in applying spatio-temporal models to map organic carbon and changes in organic carbon at a national scale illustrating my presentation with examples from the UK and France. The assumptions of stationarity in the mean and variance of a soil property that apply when using geostatistics have restricted is use at national and regional scales. New developments have been made in statistical analysis techniques which mean these assumptions do not have to apply across the whole area of interest and are demonstrated in the analysis of data from England and Wales and France. Soil organic carbon data often has large outliers due to the short scale variation in soil which can mean that standard geostatistical models can overestimate the spatial structure in the data. Robust methods are presented which allow these outliers to be identified and ways of allowing for these outliers are also presented to ensure valid maps are produced.

I will discuss the opportunities to use these methods to extend the mapping to Europe using national soil monitoring data including estimating the errors in the maps. I will also highlight the limitations and challenges of using data from different soil inventories and monitoring networks.

Modelling carbon dynamics of arable fields

Uwe Franko

Carbon sequestration in soils has been identified as a relevant process to mitigate the increase of greenhouse gas concentration in the atmosphere at least for some decades (Lal, 2004). This applies especially to arable sites as they have a remarkably lower carbon input compared to grassland and forest sites and there is a growing biomass demand for energy production that could further reduce the available carbon for SOM reproduction.

If properly validated models are a helpful tool to describe the interaction between field management, soil properties and climate and to provide a forecast of possible SOM changes due to changes in climate and farm management.

Starting with the CANDY model (Franko et al., 1995) the development went into both directions: the integration of CIPS (Kuka et al., 2007) gave new insights in the nature of SOM stabilisation due to its interaction with soil structure and the recently validated CCB model (Franko et al, 2011) provides a simple tool for application with minimized input data. CANDY and CCB are based on the same understanding of SOM dynamics characterized by the pool concept, the assumption of a general carbon reproduction flux (C_{rep}) based on crop yield as well as organic amendments and the integrated description of site conditions in terms of Biologic Active Time (BAT).

From the general approach it is obvious that BAT is a useful indicator showing the biologic activity for SOM turnover. Maps of average BAT values help to separate regions with high turnover activity that would require higher inputs of organic matter for a given SOM accumulation rate than regions with low BAT.

From the basics of the model we can deduce that the quotient C_{rep}/BAT is an indicator for the steady state content of the easy decomposable part of SOM. Despite agricultural soils may be far from steady state this indicator helps to identify regions with higher sensitivity to an intended change of cropping schemes. Mapping of C_{rep}/BAT requires some more effort because in this case additional to soil parameters and climate data also management data have to be available.

Carbon stocks of northern German soils as varied by climate and historical and recent changes in land use

Günther Springob

Sandy arable soils in northwest Germany provide a broad range of C contents or stocks in their top 30 cm (broad) while their equilibrium contents just cover a small range up to about 2.5% OC (depending on local climate). Excess OC, and thus ON, will be subject to future decay. Mapping current SOM reserves plus deriving local equilibrium contents means to derive estimates of future losses. This was the original motivation behind the presented studies, and it was primarily based on the nitrate problem in groundwater catchments (from net mineralization). For the iSOIL project (and for the COCOS workshop), the OC data is now being re-evaluated to provide independent validation data for iSOIL-derived maps of soil properties.

Detailed data will be provided for the 309 km^2 of the Fuhrberg Fields, a groundwater catchment north of Hannover, Germany. Besides arable land and grassland (earlier focus), woodland is now included as well. The mapping approach is a very pragmatic one, based on available (own) OC data from several hundred sites and on the locally available, GIS-based information like soil type, history of land-use and others. The main constraint in terms of OC storage seems to be to extrapolate the available topsoil data to the 1-m-layer. For arable land, the climatic dependence of OC stocks may also be presented.

Vulnerability of global soil C stocks

Martin Köchy and Annette Freibauer

Soil contains three quarter to four fifths of the terrestrial organic carbon pool, almost three times the amount of carbon in the atmosphere. Due to its size, small changes in the soil carbon stock can have large effects on atmospheric C concentration and hence on global warming. Previous models have not included wetlands and did not account for the thawing of permafrost soils which both have huge C stocks. In addition, previous models did not include effects of land use change. We constructed a three-pool, temporally implicit model based on categorized driver variables associated by probabilities (Bayesian Network). The model was successful in simulating existing C stocks. Differences could be attributed to inconsistencies among input data classification with regard to historic C stocks, C input (NPP after harvest), and wetland status. Simulation based on projected changes of climate and land use showed that globally, climate effects on NPP have the strongest impact on soil C. Land use, in contrast, has the greatest effect locally because the expected global extent of LU changes involving a change in growth form is small. Direct climate effects on decomposition rates were greatest in the humid tropics because of greater absolute increases in decomposition rate with higher temperatures. Regions outside the tropics are most important for the total global C stock because of the greater land area. Global C stocks are expected to increase if NPP increases due to CO_2 fertilization. C stocks are expected to remain similar or decrease if NPP is limited by N availability. For future assessments of global C stocks we suggest including the effect of high water tables on decomposition rates.

Sampling for mapping and monitoring of soil carbon stocks

Dick J. Brus and Martin Knotters

An important step in mapping and monitoring of soil carbon stocks or changes therein is sampling, i.e. the selection of locations and times on which observations are taken. Integrated planning of data collection and data processing, with respect to the required information, is crucial for efficient mapping and monitoring. Our aim is to contribute to the discussion on sampling aspects of mapping and monitoring of carbon stocks, and on sampling for validation of maps.

We distinguish two modes of selecting parts from a universe/target population: targeted (or purposive) sampling and probability (or random) sampling. If local predictions are required, i.e. mapping, then purposive sampling striving for fair spatial distribution of the sampling units is recommendable. Next, a model of spatial variation is used to interpolate to unvisited locations. If global information such as areal means, totals or proportions are required, then probability sampling is attractive. Probability sampling is recommendable if objectivity is important, because model-free estimates can be obtained. Objectivity is important in testing against (legal) standards and in validation (quality assessment). The choice for a type of design for probability sampling (e.g. stratified simple random sampling, two-stage random sampling) depends on the required information, constraints on its accuracy and on practical and budgetary constraints.

In monitoring several patterns for sampling in space and time can be applied, such as static samples, synchronous samples, rotational samples et cetera. Furthermore, four combinations of sampling modes (targeted or probability) in space and time are possible. For estimation of temporal trends in spatial means we recommend to combine probability sampling in space with targeted selection of sampling times, and to revisit at least a part of the sampling locations. We stress that taking conscious decisions on the sampling design is essential for the success of monitoring programmes for soil carbon stocks.

Proximal gamma-ray soil sensors: potential role in mapping carbon stocks

Eddie Loonstra

Proximal passive gamma ray soil sensors have proven to be very useful in the mapping of physical soil properties. Gamma ray sensors have a history in geology and the mining industry, especially in borehole conditions. With the development of mobile proximal gamma ray sensor systems in the 1990s it is also used for mapping soil properties. These passive systems are capable of measuring the gamma ray energy that is emitted by soil and rocks on-the-go. Typically, a gamma ray sensor measures the energy spectrum from 0 to 3000 keV of the radiation that reaches the surface. In general, 95% of the measured radiation originates from the top 30-40 cm of the soil.

High resolution digital soil maps of top soil can be constructed by mapping soil radionuclide concentration with a passive gamma ray soil sensor like the Mole and modelling concentration of radionuclides and values of soil properties. The Soil

Company has applied the Mole technology since 2001 and employs it to map organic matter content for instance. Experience of mapping SOC with the Mole is very limited. An indicative small study was conducted at 3 fields in Luxembourg in 2009. It was the intention to investigate whether gamma ray soil sensors could be helpful in improving the results of airborne imaging spectroscopy for the mapping of SOC.

Proximal soil sensors can be applied in global & national SOC mapping. Fore global issues proximal soil sensors can be of use in reducing the uncertainty of global models based on remote sensor imaging due to the limited resolution. It is expected that will better predict trends and stock variability compared to combined sampling & DSM. Therefore it is preferable to apply soil sensor technology for national purposes as well. Issues that have to be resolved when mapping SOC with passive gamma ray technology are the quality of the SOC models, the effects of soil types, predictability and repeatability.

Modelling the spatial stocks and composition of soil organic carbon

Jeffrey A. Baldock and Raphael Viscarra Rossel

Interest in being able to quantify the amount and distribution of organic carbon in global soils exists due to the positive contributions soil organic carbon (SOC) and its associated elements make to soil productivity and the potential role that soils may play in the abatement of net greenhouse gas emissions. However, simply defining the amount of SOC present will not be enough. To support the adoption of management practices with a capability to store additional carbon (for productivity or carbon accounting), estimates of the associated certainty or risk will be required. Sources of variability that will need to be accounted for include those associated with the sample preparation and analytical measurements, spatial variability across the landscape of interest, temporal variability in any climate, edaphic and vegetation characteristics that can impact of SOC values and finally that associated with any predictive models used. Understanding these uncertainties will lead to the development of risk profiles associated with the outcome of adopting defined management practices at levels ranging from individual farmers making business decisions through to policy makers looking direct efficient investment. The ability of infrared spectroscopic methods used in combination with multivariate statistical analyses to provide estimates of SOC spatial variations at scales ranging from individual paddocks through to the globe will be presented and discussed. The importance of understanding the composition of SOC and the benefits that this will provide will also be discussed along with how this is being addressed in Australia through a national soil carbon research project and the potential development of a soil monitoring system.

Conclusions

1. Current global maps of C stocks mainly rely on maps of well-defined soil units which are associated with soil types and soil properties frequently approximated thereof by classification and pedotransfer rules and functions. Pedotransfer rules and functions predict the value of a particular soil characteristic on the basis of other, typically more easily measurable, soil characteristics. Since pedotransfer functions are entirely empirical in nature, it is preferable that they be derived from soils that are similar in nature to the soils to which the functions will be applied. This mapping method is widely accepted, considers the pedogenic factors, but is limited to generalized and predefined conditions. Although some soil profile data are outdated and pedotransfer rules and functions are sometimes applied beyond their calibration range, such functions are often the best methods available to derive estimates of soil properties (e.g., soil carbon content or stock) for poorly sampled or remote regions. The method is suitable for assessing vulnerability and identifying hotspots, but is not satisfactory for mapping current status of C stocks and actual dynamics.
   1. Classification of soils produces uncertainty in the reported carbon stock when the characteristics of soil classes are aggregated and then used in further calculations.
   2. The use of pedotransfer rules and functions further increases the uncertainty of the real values.
   - ➢ **C stocks must be given with quantified uncertainty to be useful for purposes of detecting actual change.**
2. Current global maps of C stocks do not yet include all existing soil profile data, but are mainly based on the WISE data set with currently (v. 3.0) large gaps in Asia, northern Africa, Canada, Australia, and northern Europe. Many soil profile data collected by governments and publicly funded projects remain unused because they are not available digitally, their use is restricted because of data privacy, or only a few people know of their existence. There are several well-organized approaches like the Northern Circumpolar Soil Carbon Base, the GlobalSoilMap.net project, and coordinated by FAO, the upcoming Global Soil Partnership. Additional networks for soil parameters, e.g. the Globally Distributed Soil Spectral Library and Open Soil Profile, have emerged. There is a high potential and level of activity to collect, harmonize and use the wealth of soil data available around the world by enhanced cooperation. Global cooperation among stakeholders also contributes to improving harmonization of sampling, measurements, and data processing.
   1. Current global maps of carbon stocks are based on limited profile data.
   2. Profile data and maps have been generated by a multitude of methods causing inconsistencies and additional variability.
   - ➢ **Digitalization of paper maps and profile data (e.g. World Soil Survey Archive and Catalogue) should be funded so that products become available within 50 years after their original measurement.**
   - ➢ **All publicly funded, existing soil profile data should be made publicly available. If legal requirements prevent full public access, data should be made accessible in a different form (e.g. not geo-referenced, aggregated, as pedotransfer function).**

   - **International activities to harmonize methods of sampling, calculation, and scaling should be supported. Harmonized methods should be applied in soil sampling.**

3. Predictive mapping techniques, including geostatics, modelling, and other quantitative methods, as a substitute for soil-unit based mapping have rapidly progressed in the last five years so that these methods are applicable to map soil properties directly as a function of multiple covariates. These approaches can potentially reduce uncertainties in carbon mapping introduced by soil classification and help interpreting spatio-temporal patterns.
   1. The choice of appropriate covariates in predictive mapping is important.
   2. The choice of the predictive method has less impact on the overall error as different approaches will lead to similar results. In contrast, the way in which the predictive methods are applied have a great effect on the result.
   - **Minimum requirements and guidelines for predictive methods are needed for making maps comparable.**
4. Proximal sensing (including radiometry, NIR spectroscopy) and remote sensing (hyperspectral remote sensing) are interesting methods to determine organic carbon at various soil depths (mainly surface, topsoil) in a spatially contiguous way. A range of spectroscopic approaches (e.g. mid-infrared spectroscopy coupled to partial least squares analysis), show promise as a rapid and cost effective means to measured soil carbon content, soil carbon composition and a range of other soil properties (e.g. clay content) simultaneously with defined uncertainty.
   1. Proximal and remote sensing approaches to measure soil C need good calibration by soil inventories.
   - **A clear strategy to do the calibration for large-scale application needs to be developed and implemented.**
   - **Further research defining the suitability of spectroscopic methods combined with multivariate analyses to predict carbon concentration and composition should be completed.**
5. A diversity of methods and combination of old and new approaches characterizes the near future of soil mapping. Therefore, calibration and validation is critical for all types of maps.
   1. Validation against soil profile data is a measure of map quality.
   - **The method of validation should be related to the purpose for assessing the suitability of maps for certain purposes.**
   - **For practical purposes the quality of a map should be translated into the risk of taking wrong decisions.**
6. The experience of long-time soil scientists and surveyors is an important resource for interpretation and assessment of geostatistical approaches and proximal and remote sensing. Plant and soil scientists would benefit from closer cooperation for understanding characteristics of soils.
   - **Rely on, conserve, and use the knowledge of old field soil scientists (e.g. by twinning with novices, give them a role in training and education).**
   - **Maintain good education for the next generation of soil scientists.**
7. Soil monitoring is crucial for detecting changes in soil C stocks.
   1. Extra care is necessary to reduce variability of data because variability reduces the detail of detecting change.
   - **Carbon concentration, bulk density, and coarse fragments must be measured at the same point or sample to reduce effects of spatial variability.**

Soil must be measured in meaningful depth increments. Sampling points must be marked for revisits.

- **Knowledge of soil horizons and organic layers is necessary for decision on sampling depths and interpretation of the data.**
- **Samples must be archived so that soils can be reanalyzed with improved or new methods or for checking data by more than one laboratory.**
- **Field sampling should be combined with as detailed as possible information about land use, land cover, crop type, land use history and land management for assimilating data in models.**

8. For assessing risk of carbon stock losses, current carbon stocks are the best predictors. Carbon may be stabilized by water saturation, frost, or carbon form (charcoal). The derivation of soil carbon composition data simultaneously with other soil properties by spectroscopic approaches with defined uncertainty and their use as inputs to soil carbon cycling models would facilitate scenario predictions of management impacts on soil carbon stocks.
    1. Lack of data and knowledge about subsoil carbon (> 1 m) restricts our assessment of change of carbon over time in organic soils.
    2. At local to global levels, water saturation, peat thickness, and active layer depth of permafrost is critical for loss of carbon stocks.
    - **Mapping of soils should be coordinated with the direct or indirect mapping of carbon input and its controlling factors, and extent and soil depth of wetlands, peatlands, and permafrost. FAO or GEO (which recognizes soil carbon as a terrestrial Essential Climate Variable) would be suitable coordinating agencies.**
    - **Assessment of the usefulness of carbon composition (fractions) as inputs to soil carbon cycling models is required across global soils.**