GSP Guidelines for sharing national data/information to compile a Global Soil Organic Carbon map (GSOC17)

GSP Secretariat/ITPS Working Group on Soil Carbon

19 September 2016

Summary

This document provides definitions and guidance for the global soil carbon mapping activity which the Global Soil Partnership (GSP) and Intergovernmental Technical Panel on Soils (ITPS) committed to undertake in the framework of its cooperation with the United Nations Convention to Combat Desertification (UNCCD) and its Science Policy Interface (SPI).

The GSP partners are engaging in a global soil carbon (GSC) mapping activity, which is primarily based on existing soil carbon maps and measurements. A GSC map will be produced based on existing national soil carbon data. This activity is closely linked to the development of the Global Soil Information System under GSP Pillar 4 on Soil Data and Information. Due to the urgency for action and the envisaged cooperation across United Nations (UN) conventions as a contribution to the sustainable development goals (SDGs), this activity is pursued with high priority.

This document provides background and detailed specifications about the required data sources and methodologies.

Part I: Background and task

1. Improving global soil carbon information through the Global Soil Partnership

The Global Soil Partnership (GSP) cooperates very closely with various global mechanisms which address soil issues and which require improved information collection and sharing about the status of soils. This cooperation is important because FAO member countries are involved in various global activities through monitoring and reporting on natural resources, including soils, and it is import to align these activities to improve knowledge and information exchange about soils. The quality of soil carbon information at global level is still limited because much existing national information has not yet been shared for global compilation. A precise and reliable global view on soil organic carbon (SOC) is needed under different UN conventions, such as on climate change and desertification, but especially as part of the Sustainable Development Goals (SDG). For example, under the Framework Convention on Climate Change (UNFCCC), countries address soils and soil carbon in their national greenhouse gas inventories. Under the Lima-Paris Action Agenda, the 4 per 1000 Initiative supports the role of carbon storage in soils to mitigate and adapt to climate change. To assess the amount of degraded land under sustainable development goal (SDG) 15.3.1, soil carbon is an important component under the sub-indicator on above and below ground carbon.

2. Request for soil carbon mapping

The GSP is currently tasked to provide support on soil carbon issues. FAO and the GSP Secretariat were recently approached by the United Nations Convention to Combat Desertification (UNCCD) Secretariat to share information about the GSP and the possible pathways to contribute to improving soil carbon knowledge and data. During the 5th Session of the GSP's Intergovernmental Technical Panel on Soils (ITPS) held during March 2016 (http://www.fao.org/global-soil-partnership/intergovernmental-technical-panel-soils/fifth-working-session/en/), collaboration between ITPS and the Science Policy Interface (SPI) of the UNCCD, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), and the Intergovernmental Panel on Climate Change (IPCC) was discussed. GSP/ITPS were requested to conduct a global SOC assessment based on country-level spatial soil data sets, combined to a new global SOC map. As an action of the GSP and its members, this task would directly relate to SDG 15.3.1, and would also support the endorsed metrics for the assessment of land degradation neutrality (LDN). The issue of soil carbon mapping through the GSP was also discussed and supported during the 4th GSP Plenary Assembly, May 2016 http://www.fao.org/documents/card/en/c/db9c281e-a17f-4e11-91c9-64edfcf54dc6/ .

The Global Soil Partnership has been requested to develop a global soil organic carbon mapping by 2017.

Part II: Functions of soil carbon and the role of soil carbon mapping

3. The importance of soil carbon

Soil organic matter (SOM) is composed of about 58% carbon and is a crucial soil component which affects most of the processes relevant to soil functions and food production. Changing SOM (and hence SOC) affects the capacity of soils to buffer against environmental change and changes the provision of ecosystem services required for crop production. SOM therefore regulates the resilience of the agricultural system to climate change.

SOC has received great attention during the development of the greenhouse gas (GHG) reporting programme of the IPCC since the mid-nineties. This was done to address the contribution of intensive land management and the vast amount of degraded land to GHG emissions, since these have caused tremendous historic losses of SOC, resulting in high potentials for future carbon storage. Recently, an increasing number of authors have stressed the crucial role of healthy soils, with soil carbon being the most important indicator, for food security and resilience against climate change. Hence, above- and belowground carbon (SOC) became sub-indicators for SDG target 15.3.1 (degraded land).

The 2015 Status of the World's Soil Resources (SWRS) report[1] highlights that, although more carbon is stored in soil than in the atmosphere and plant life combined, a large portion (33%) of the world's soils are degraded and organic matter has been lost. The reversal of soil degradation through the build-up of SOM and the sustainable management of soils therefore offers large potential to contribute to climate change mitigation by sequestering atmospheric carbon into the soil. In addition, this process would increase the capacity of soils to buffer against climate change which, in turn, would improve the resilience of agricultural systems to climate change.

4. Improvement of data on SOC

Despite the attention given to SOC, as described above, knowledge about SOC baselines and changes, and the detection of vulnerable hot spots for SOC losses and gains under climate change and changed land management is still fairly limited. Accurate baselines are still missing for many countries, and estimates about the role of soils in the global carbon cycle are still only based on rough estimates with large uncertainties. Global SOC estimates exist, but there is high variability in reported values among authors, caused by the diversity of different data sources and methodologies (Henry et al., 2009)[2]. Despite these existing data sources, the size and dynamics of the global SOC pool is still fairly uncertain.

Currently, countries report greenhouse gas (GHG) emissions under the UNFCCC and the Kyoto Protocol; it is optional to include reporting on SOC (other C pools are litter, dead organic matter, above- and belowground biomass) in addition to land-use change and emissions from organic soils. Currently, few countries report on SOC. In addition to GHG inventories, UNFCCC has prepared guidelines for carbon accounting in Clean Development Mechanism (CDM) projects. However, due to difficulties in harmonizing sampling, measurements and accounting for SOC change, very often no-change is assumed for SOC, thus no data are reported. It is likely that, due to the increasing importance of SOC for the global terrestrial GHG cycle, countries have increased interest (and may reach respective agreements in future UNFCCC negotiations) to improve reporting on SOC pools. This is especially true because there are large carbon storage potentials created by unsustainable management, land-use change and land degradation; increasing SOC levels also improve the resilience of soils to climate change effects (e.g. drought; increased SOC improves various soil functions including water holding capacity and nutrient

[1] ITPS. 2015. Status of the World's Soil Resources Report.

[2] Henry, M., R. Valentini and M. Bernoux (2009). Soil carbon stocks in ecoregions of Africa. Biogeosciences Discuss. 6: 797–823.

availability). Efforts to increase SOC by increasing organic matter levels in soils require baseline data (location of degraded sites, hot spots for restoration) in order to plan action on the ground, and monitoring in order to verify that the intended effects are achieved. In order to estimate baselines and changes of SOC per land area, very often in GHG inventories, typical values for soils under certain land use are used (Tier 1 and Tier 2; see below). However, this is still very coarse, and many scientists warn that this approach would not provide reliable estimates of SOC changes after land use change. It is thus recommended to improve the knowledge about SOC through the development of a high-resolution spatial assessment of SOC as a baseline.

With regard to existing national SOC estimates, Henry et al. (2009) conclude that the quality of spatial estimates of SOC[3] largely depends on number of soil profiles, the quality and resolution of soil maps, and the quality of data available to derive carbon stocks; besides SOC concentration, it requires the soil bulk density, and the amount/proportion of coarse fragments [rock/stone content]. They also advise to use soil maps with the highest resolution possible.

5. Objectives for soil carbon mapping

5.1 Global SOC map

GSP members will jointly develop a global SOC map as a baseline for the amount and distribution of SOC in soils around the world. This map will be developed following the general GSP principle of being a country-driven initiative. It will be part of the process to build a Global Soil Information System under GSP Pillar 4 (Enhance the quantity and quality of soil data and information: data collection [generation], analysis, validation, reporting, monitoring and integration with other disciplines). The endeavor will further consider the following aspects:

- Definitions relating to SOC and SOC change elaborated from the IPCC definitions
- GSP data sharing mechanisms
- Quality assured, harmonized and validated data sets, which may become officially shared as the nationally representative SOC data

This concept builds on official national data sets, therefore, a bottom-up (country-driven) approach is pursued which offers a new quality to the future global assessment of soil indicators.

[3] (amount of C per area, based on a mapping of SOC for a defined area)

5.2 Map components

The new global soil carbon map will have the following product components:

Product	Abbrev.	Specifications	Description (see Part 3, Chapter 8 for details)
Map of global SOC stocks	SOC_{stock}	0-30 cm depth 1 km resolution	– **Depth class 0-30 cm**: sub-divisions in thinner depth slices, or extensions beyond 30 cm depth are acceptable, depending on national sampling strategies and available data; – Calculation of **C stocks**: requires data about the SOC concentration, bulk density and stone content – Calculations for **organic soils** may differ from **mineral soils**: in organic soils, the dry weight of organic material in the depth 0-30 cm, or a proper extension factor, is required.
Map of global SOC concentrations	SOC_{conc}		– A SOC concentration map, separate from the SOC stock map, could be easily developed because SOC concentrations are input data for SOC stock calculations.
Uncertainties	SD	Standard deviation	Based on measurements, metadata and documentation, the quality of information can be assessed (measured, estimated, and statistically calculated). In order to conduct a complete uncertainty assessment, information about the density of sampling points is needed.

The following three procedural steps are foreseen:

1. Countries may share existing national SOC maps
2. Should national SOC maps not exist or not conform to the specifications, countries may produce national SOC maps initiated by this project
3. Should countries not have the capacity to produce national SOC maps, they may elect to share original SOC measurements (point samples such as soil profiles) with the GSP Secretariat which will organize the production of the national SOC map in close consultation with the country representatives.

5.3 Compatibility with other specifications and guidelines

It has to be ensured that the **GSP objectives** are considered when building a grid-enabled spatial data infrastructure for soils (Pillar 4, version 0 and version 1 soil grids) and that the product specifications are compatible with other spatial thematic layers shared under the **Global Earth Observation System of Systems (GEOSS)**, **United Nations Spatial Data Infrastructure (UNSDI)**, and others such as the new framework for **SDG indicator assessments**.

The specifications for this product do not only comply with IPCC specifications (in order to fit national GHG reporting efforts and thus to use synergistic effects with existing activities), they also consider the **Global Soil Map (GSM) specifications**. Under GSM, six standard depth intervals of 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm are recommended. Thus, the 0-30 cm depth class for this global SOC map could be derived by adding the three uppermost depth classes. If digital soil mapping is applied for SOC mapping (see also Ch. 8.4.4), the GSM specifications can be directly applied as a further detailed technical specification for SOC mapping. These specifications were also recommended for use in GSP Pillar 4.

6. Benefits

The development of a global SOC map according to this guideline provides and builds on synergies with ongoing and new reporting needs and data sharing obligations and therefore benefits activities at national, regional and global levels to:

- Enable training for countries in need of technical support (e.g. regarding the collection, statistical evaluation and modelling of SOC data)
- Develop data to update the SWRS report on SOC through a country-driven baseline, and to initiate future assessments of SOC change
- Support national GHG reporting: develop a valid, measurement-based inventory of reference SOC stocks for **IPCC-Tier 2 assessments** baseline (see Chapters 4 and 7)
- Further utilize SOC mapping to estimate the **soil carbon sequestration potentials** (e.g. through modeling) and the **vulnerability of soil functions under climate change** (with SOC as indicator)
- Contribute to the **Sustainable Development Goals**: to develop national SDG-15.3.1 Tier 3 data for the sub-indicator of soil carbon
- Conduct harmonized assessments at different levels of action: GSP regional soil partnerships: FAO regional and country offices, national soil information institutions (GSP Pillar 4 INSII), national statistics offices (already involved with FAOSTATs), and GEOSS design principles for global data layers.

7. Definitions

7.1 Soil Carbon in UNFCCC reporting

a) Terrestrial carbon pools and reporting methods for UNFCCC greenhouse gas inventories, following IPCC guidelines

IPCC (2006)[4] defines different terrestrial carbon pools, including carbon stocks in mineral (inorganic) and organic soils, focusing on carbon stock changes over a reporting period. Thus it has established definitions to monitor soil carbon as agreed by reporting countries. This framework can provide guiding principles for global SOC mapping by the GSP because (a) a SOC map allows the derivation of basic national default values for SOC, and (b) the new global SOC map could serve as a baseline for future assessments about SOC changes (monitoring, see also: SWRS report).

IPCC (2006) provides methods to estimate greenhouse gas emissions and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sectors. It includes the reporting of carbon stock changes for five terrestrial storage pools by land-use category (Forest Land, Cropland, Grassland, Wetlands, Settlements, and Other Land). The carbon pools are: above-ground biomass, below-ground biomass, deadwood, litter, and soils. Carbon stock changes are estimated for strata or subdivisions of land area (e.g., climate zone, ecotype, soil type, management regime etc.).

Two general approaches for reporting carbon stocks and changes are suggested:

1. Process-based approach: annual carbon stock changes in the pool (Gain-Loss Method)
2. Stock-based approach (Stock-Difference Method)

The Gain-Loss method is based on knowledge about a typical carbon stock (baseline) for a certain land use: the area of land category is multiplied with an annual C-stock gain or loss, or baseline default

[4] IPCC (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

values are multiplied with a stock change factor (e.g. emission factor after management change or land use conversion). The stock-difference method relies on the difference of SOC estimates at two points in time.

IPCC distinguishes three Tiers. Tier-1 methods apply generic default values and emission factors from literature. It includes several simplifying assumptions, e.g. dead wood and litter are often lumped together as 'dead organic matter', and its net stock change is zero. For Tier 1 and 2 methods, soil organic C stocks for mineral soils are computed to a default depth of 30 cm. Greater depths may be selected and used if data are available (Tier 2 and Tier 3).

b) IPCC definition of SOC

The soil carbon pool includes carbon in mineral soils to a specified depth chosen by the country and applied consistently through the time series. The **default soil depth is 30 cm** (guidance on determining country-specific depths is given in Chapter 2.3.3.1 of the IPCC Guidelines). However, "*it is good practice to derive reference C stocks to a greater depth if there is sufficient data, and if it is clear that land-use change and management have a significant impact over the proposed depth increment*." SOC is included in organic material (living and non-living) within the soil matrix, operationally defined as a specific size fraction (e.g., all matter passing through a 2 mm sieve). For forest soils, this definition may include layers of the forest floor with high levels of fine humus (F and H horizons).

Litter, which belongs to the dead organic matter pool, "*includes all non-living biomass with a size greater than the limit for soil organic matter (suggested 2 mm) and less than the minimum diameter chosen for dead wood (e.g. 10 cm), lying dead, in various states of decomposition above or within the mineral or organic soil.*"

National circumstances may require modifications of the pool definitions.

For forest soils, some national SOC data sets may thus include parts of the forest floor. This SOC mapping project will – in order to be consistent with national UNFCCC definitions – also include the forest floor, except litter defined as the L horizon plus fine woody debris. Metadata provided by the countries thus need to specify national definitions of SOC (depth class, mineral soil, litter in the case of forests, organic and inorganic carbon, shallow peat etc.).

c) Reference carbon stocks

Country-specific reference C stocks can improve GHG inventories (Tier 2) by being more accurate and representative. Country-specific reference soil C stocks are derived from measurements of soils, "*for example, as part of a country's soil survey. It is important that reliable taxonomic descriptions be used to group soils into categories. There are three additional considerations in deriving the country-specific values, including possible specification of country-specific soil categories and climate regions (i.e., instead of using the IPCC default classification), choice of reference condition, and depth increment over which the stocks are estimated.*

Soil carbon stocks are computed by multiplying the proportion of organic carbon (i.e., %C divided by 100) by the depth increment (default is 30 cm), bulk density, and the proportion of coarse-fragment free soil (i.e., < 2mm fragments) in the depth increment. The coarse fragment-free proportion is on a mass basis (i.e., mass of coarse fragment-free soil/total mass of the soil)."

d) Experiences with SOC mapping according to IPCC

The current reporting practice for LULUCF (Land use, Land-Use Change and Forestry) in Europe was recently evaluated by Blujdea et al. (2016)[5]. Twelve European Union (EU) member states report on SOC in forests using a Tier 3 approach, five countries use models (gain-loss), and seven countries use inventories (stock-based). In most cases, forest SOC maps were very likely produced in order to quantify and project the SOC stock assessment for the whole country. As for Grassland/Cropland, 20 countries have been reporting according to Tier 2 specifications. SOC maps for agricultural land are thus expected to be scarcer.

This project will compile national, spatial SOC assessments for all land uses. This may require that countries with higher Tier assessments for forest soils only, compile national data for all land uses and re-calculate the national SOC map for all land uses.

7.2 Generic definition of SOC and SOM from literature

SOM definition: Soil organic matter (SOM) is the fraction of the soil that consists of plant or animal tissue in various stages of decomposition. SOM is made up of different components that can be grouped into three major types: (1) Plant residues and living microbial biomass, (2) Active soil organic matter also referred to as detritus, and (3) Stable soil organic matter, often referred to as humus. The major chemical element present in SOM is carbon bound in various organic compounds which is commonly referred to as SOC. If the analytical method determines total carbon, then, for calcareous soils, the mineral carbon content needs to be determined and subtracted in order to avoid overestimations of SOC.

Relationship between SOC and SOM: Although the content of carbon in SOM may vary, on average SOM contains about 58% of carbon (Van Bemmelen factor: 1.724). For organic horizons (forest floor, peat), values may significantly differ (see also Nelson and Sommers, 1982[6], who provide ranges of 1.9 – 2.5 for soil horizons rich in SOM). With decreasing levels of humification, the conversion factor approaches 2 (e.g. F horizons of the forest floor).

A generic definition and description of SOC and SOM is also contained in IPCC, 2006 (Ch. 1.2.1, Science Background). The definition provides deeper insight into the processes that lead to gains and losses of SOC in soils.

[5] Blujdea, V.N.B., R. A. Viñas, S. Federici and G. Grassi (2016): The EU greenhouse gas inventory for the LULUCF sector: I. Overview and comparative analysis of methods used by EU member states, Carbon Management, DOI: 10.1080/17583004.2016.1151504

[6] Nelson, D. W. & Sommers, L. E. (19821. Total carbon, organic carbon, and organic matter. In Methods" of Soil Analysis, Part 2, ed. A. L. Page. Agronomy No. 9, Monograph Series, American Society of Agronomy, Madison, Wis., pp. 539-79.

Part III: Specifications for soil organic carbon mapping

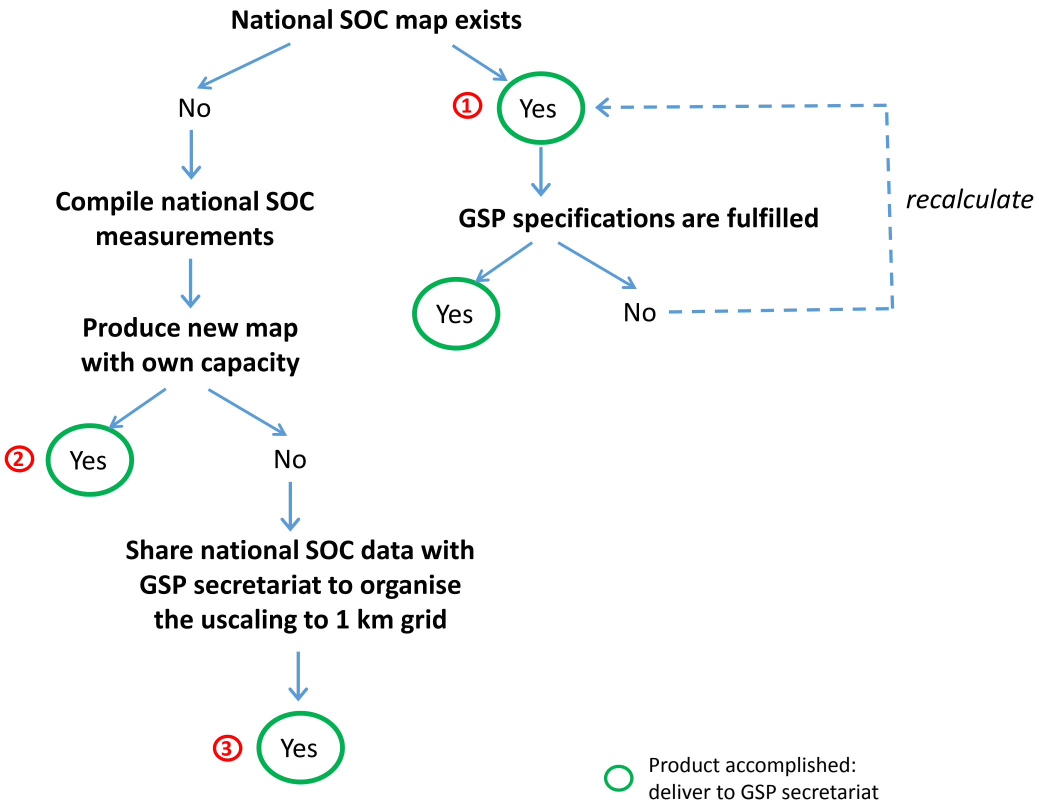
8. Specifications for the global SOC map

8.1 Generic target specification

- Grid 1x1 km (generic grid will be provided and higher resolutions are acceptable)
- Various SOC analysis methods and measurements are acceptable
- 0-30 cm depth, including national increments and/or higher (deeper) depths where applicable
- SOC stock: BD and stone content can be derived or measured
- Mapping/upscaling: various approaches possible (including country-specific stratification and custom resolution finer than 1x1 km)

8.2 Country-driven action

The following three basic approaches for the voluntary sharing of national SOC data are possible, based on country data availability and capacity:



1. Compile existing national SOC maps

Should countries already have national SOC maps which meet the specifications of this project, these may be shared for this global SOC mapping project. If a national SOC map exists, and if not all requirements are met, adjustments of the existing SOC map may be implemented if this is possible (e.g. recalculation according to target depth). Any other relevant national information about SOC-related evaluations, calculations and reports (e.g. SOC in UNFCCC reporting), shall be shared with the GSP secretariat as meta information. This includes methodological information (e.g. distribution of soil profiles; upscaling method) in order to allow an uncertainty assessment.

In countries where national SOC maps are not available or existing SOC maps do not meet the specifications, refer to approach 2:

2. **Countries may develop new or updated SOC maps**

   Countries which do not yet have a national SOC map, may develop such a map based on the specifications recommended here (see also Annex 2, Cookbook for SOC mapping, to be supplemented later). As mentioned under Ch. 6 (Benefits), and similar to approach 1, this would enable countries to derive national IPCC default values for SOC (i.e. typical SOC values for soil types, soil-climate-land cover types, or other stratification). Where needed, FAO, with the help of its national and regional offices, will attempt to bilaterally support such national activities.

   If the in-country development of a SOC map is not possible (perhaps due to insufficient capacity), refer to approach 3:

3. **Countries are encouraged to share original national SOC measurements (point-locations: soil profiles or auger sampling) with the GSP secretariat**

   Typically, the measurement of SOC requires the sampling of soils in the field at a certain location ("point data" compared to map data, presented in the form of polygon maps or grids). In order to allow for a national SOC map, such point data require upscaling. Where no national capacity exists to conduct such an upscaling exercise, the original SOC measurements may be shared with the GSP secretariat which would then execute the upscaling in close cooperation with the national GSP-focal points and/or institutional data providers. Countries may decide whether shared soil profile data may enter the GSP Pillar 4 Tier 1 and/or Tier 2 soil profile databases or not.

If there are countries with a complete lack of SOC measurements, a sampling campaign may be conducted in representative soil types under typical land use. Due to the limited time available to produce the global SOC map, however, this cannot be done in a sufficiently representative manner.

8.3 The GSP community of practice

The GSP represents a wide *community of practice*[7] including 135 official country representatives and 225 members from non-governmental organisations. Well-aligned action in nine regional partnerships covers a wide variety of soil-related topics across the globe. To build the Global Soil Information System (GSP Pillar 4), an international network of soil information institutions (INSII) has been established. This network is still in its starting phase and is continuously growing (currently consisting of 60 countries/institutions). It will allow the exchange of new, harmonized national data as part of new global data sets including soil profile data, soil polygon maps, soil property grids and the monitoring of indicators (SoilSTAT). The GSP (Pillar 4) and INSII are the facilities through which the task of a global SOC map can be developed. The development of the Global Soil Information System, including soil monitoring, is accompanied and advised by the ITPS.

[7] Soil researchers, soil inventory experts, politicians, farmers, agricultural industry, education

8.4 Detailed specifications and metadata

The following specifications provide an overview of the methods to be used to determine SOC stocks and develop SOC maps. The project will allow for all given national modifications (definitions, methods, resolutions) even though this may introduce a significant portion of bias for the global assessment. Data will be shared and extensively documented to enable quality and uncertainty assessments. This will allow insights into the quality of the SOC maps, remaining gaps and harmonization needs.

The specifications listed below may provide guidance to those countries lacking previous SOC assessments, but also guide the documentation of the national methodologies. A template will be included in the cookbook for SOC mapping (Annex 2; to be provided later).

8.4.1 Data sources for SOC mapping

Data sources to produce SOC maps can be any relevant measurements on soil samples, i.e. data from soil augers or soil profiles. In most cases, these data are derived from previous field campaigns (legacy data: see also 3.3.5). Meta data about the available data sources include the following:

Specification 1:	Share auxiliary information about the national data sources, e.g. type of sampling (soil profile or auger), density of sampling points in the country, sampling design (distribution and sampling depth/s), time of sampling (year), selection criteria (if subset of soil profiles is selected from a larger national database).

8.4.2 Analytical methods to determine SOM and SOC

All national SOC maps will be based on existing soil sampling and analyses. There are three common types of SOC analysis as described below, but all types of analyses will be accepted; however, the methods used needs to be well-documented wherever possible.

a) Total soil carbon from dry combustion with higher temperatures (elementary analysis)

With this method, the total soil carbon is determined with temperatures > 600-800°C, hence for calcareous or limed soils the proportion of $CaCO_3$ in the mineral soil has to be determined and subtracted in order to obtain the amount of organic carbon (inorganic carbon is also oxidized). The standard analysis is described in ISO 10693 (1994)[8]. It refers to the Scheibler volumetric method with hydrochloric acid (HCl). The pH value gives the first indication whether the sample has to be analyzed for inorganic carbon. The European ICP Forests soil manual suggests thresholds of pH($CaCl_2$) > 5.5 in the organic layer of the forest floor and >6.0 in the mineral soil.

Rosell et al. (2001)[9] concluded that the determination of SOC from dry combustion methods is the least susceptible to errors compared to many other methods.

b) Total soil organic matter (SOM) (dry combustion by Loss on Ignition)

Loss on ignition (LoI) is a dry combustion method using a furnace followed by the calculation of the difference in weight of the sample before and after the heating. LoI determines the amount of soil organic matter (SOM). SOM values based on LoI are very common since LoI represents a classic and easy-to-apply method.

[8] ISO 10693 (1994). Soil Quality – Determination of the carbonate content – Volumetric method. International Organization for Standardization, Geneva, 7 p.

[9] Rosell, R.A., J.C. Gasparoni and J.A. Galantini (2001). Soil Organic Matter Evaluation. In: Lal, R., J.M. Kimble, R.F. Follett and B.A. Stewart (eds.). Assessment Methods for Soil Carbon. CRC Press LLC P. Lewis Publishers, Boca Raton, USA. p. 311-322.

Since typically, temperatures between 400 and 550°C are used, the inorganic carbon is not determined and does not need to be accounted for. SOC is derived from applying a conversion factor - the classic conversion factor is 1.724, which is known to be incorrect for organic layers.

c) SOC from wet oxidation

Organic carbon is obtained after oxidation with a dichromate-sulfuric acid mixture. The most important method is that of Walkley and Black (1934)[10], where organic carbon is oxidized only by the dichromate, heated at 120°C. A correction factor ("oxidation factor") is needed because oxidation at this temperature is incomplete. The factors can range from 1.19 to 1.40 depending on the soil and even soil horizon (Nelson and Sommer, 1982)[11]. The most important modification of the Walkley and Black method was done by Tjurin (1931)[12].

Specification 2:	In order to estimate the quality of the global SOC map, as much metadata as possible are needed, for example about the SOC analysis method/s (for large data sets, most likely, different variants of soil analysis may apply) – Examples: type of analysis (a, b, c or other); type of apparatus; temperatures used; in case of wet oxidation: method and variations*); sample treatment (storage conditions: frozen, air-dried, stored in a moist, cool storage, and storage length), sample preparation: grinding or cutting (and thresholds for particle sizes) – For calcareous soils: report whether and how inorganic carbon was analysed. *) heating temperature and length of heating, titration agent and amount, sample weight, CO_2 determination (titrimetric (less accurate), photometric)

8.4.3 Calculation of SOC stocks for sampling locations and target soil depth

The amount of fine earth is one of the basic parameters to estimate SOC stocks in the mineral soil as well as in peat layers. This amount depends on the volume of soil considered (depth x reference area), the bulk density (BD) of the soil, and the stone content. BD expresses the soil weight per unit volume. Slight over- or underestimations (in the bulk density and amount of stones, and consequently in the amount of fine earth) can have a strong impact on the stock estimates. The estimation of stoniness is difficult and time consuming, and therefore not carried out in many soil inventories, or only estimated visually in the profile (Vincent and Chadwick, 1994)[13]. For further literature, see also Grossman et al. (2001)[14] and De Vos et al. (2005)[15].

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[10] Walkley, A. and I.A. Black (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37: 29-38.
[11] Nelson, D.W. and L.E. Sommers (1982). Total carbon, organic carbon and organic matter. p. 539-537. In: Page, A.L. et al. (eds.), Methods for soil analysis. Part 2. Chemical and microbial processes. America Society of Agronomy, Madison, Wisconsin, USA.
[12] Tyurin, I.V. (1931). A modification of the volumetric method of determining soil organic matter by means of chromic acid. Pochovovodenye 26: 36-47.
[13] Vincent K.R. and O.A. Chadwick (1994). Synthesizing bulk density for soils with abundant rock fragments. Soil Sci. Soc. Am. J. 58: 455-464.
[14] Grossman, R.B., D.S. Harms, D.F. Kingsbury, R.K. Shaw and A.B. Jenkins (2001). Assessment of soil organic carbon using the U.S. soil survey. In: Lal, R., J.M. Kimble, R.F. Follett and B.A. Stewart (eds.). Assessment Methods for Soil Carbon. CRC Press LLC P. Lewis Publishers, Boca Raton, USA. p. 87-104.
[15] De Vos, B., M. Van Meirvenne, P. Quataert, J. Deckers and B. Muys (2005). Predictive quality of pedotransfer functions for estimating bulk density of forest soils. Soil Sci. Am. J. 69.

The following approaches may be used to derive bulk density:

a) BD could be measured after sampling (report if stones were present in top soil samples, and thus in the sampling cylinders, and whether these were considered or not)
b) Calculated using appropriate pedo-transfer functions (provide reference to specify which function or estimation method was used)
c) Use of default values from literature (provide citation, level of disaggregation)

Approaches to derive the stone content include:

a) Direct measurement from soil samples (weight of stones in a sample of known volume; if used, provide method and thresholds for material sizes)
b) Estimated during field work (if the stone content has been estimated using %-classes, it would be important to share the class codes)
c) Cited values from literature (e.g. typical values per soil type and depth (provide sources)

Target depth:

If data are available for soil horizons, or according to country-specific depth classes, additional calculations have to be made to refer values to a soil block of 0-30 cm (see also Batjes, 2010[16]). In order to allow a user friendly conversion algorithm, existing solutions will be analysed and, if necessary, modified (e.g. with the statistical R software: Filippa, 2013: A package to consistently represent soil properties along a soil profile. http://rpackages.ianhowson.com/cran/soilprofile/).

Formula to determine the SOC stock:

The following formulas are used to determine the SOC stock in different soils:

a) Mineral soils

$$SOC = d * BD * (C_{tot} – C_{min}) * CF_{st})$$

where:
SOC = soil organic carbon [kg/m^2]
C_{tot} and C_{min} = total and mineral (or inorganic) carbon [g g^{-1}], to be considered for calcareous soils, and if dry combustion is used with typically high temperatures (otherwise: C_{tot} equals C_{min})
d = depth of horizon/depth class [m]
BD = bulk density [kg/m^3]
CF_{st}= correction factor for stoniness and gravel content (1-(%gravel + %stones)/100)

b) Organic layers (forest floor):

$$SOC_{forest\ floor} = weightOR * (C_{tot} – C_{min})$$

where:
$SOC_{forest\ floor}$ = soil organic carbon in the forest floor [kg/m^2]
weightOR = dry weight of the forest floor material sampled [kg/m^2]
C_{tot} and C_{min} = total and mineral (or inorganic) carbon [g g^{-1}], to be considered for calcareous soils, and if dry combustion is used with typically high temperatures (otherwise: C_{tot} equals C_{min})

c) Organic soils/peat:

The inventorying of peat is rather difficult. In order to calculate C stocks for peat, it is necessary to know the extent (area) of peat (and peat types), the depth of peat, %C and bulk density. Values for typical C concentrations and densities of peat types may be taken from literature.

[16] Batjes, N.H. (2010). A global framework of soil carbon stocks under natural vegetation for use with the simple assessment option of the Carbon Benefits Project system. Report 2010/10. Carbon Benefits Project (CBP) and ISRIC – World Soil Information, Wageningen.

Specification 3:	Share metadata about SOC stocks calculation in terms of: a) Modelling the reference soil depth 0-30 cm (if derived from soil profile sampling) b) Bulk density: measured and/or estimated, provide method description c) Coarse fragments: measured and/or estimated, provide method description d) Stratification

8.4.4 Spatial dimension: upscaling approaches

A SOC map relies on the upscaling of measurements taken from field locations. In GHG reporting under UNFCCC, changes in the SOC stock as total stock per country is needed. For that, the extent of SOC stocks per spatial unit needs to be quantified. For that purpose, very often, SOC maps were produced, referring to 1990 as a baseline (even though measurements originated from different points in time).

a) Basic methodologies

There are many possible upscaling procedures. All procedures will be accepted for the global SOC map as long as the depth dimension (0-30 cm) and the minimum spatial dimension (grid/raster 1 km) is fulfilled. However, the preferred upscaling method is digital soil mapping (DSM). In contrast to conventional upscaling, DSM allows the quantification of uncertainties. In addition, DSM-based SOC maps would conform to Pillar 4 specifications for soil grids (thus also GSM specifications).

The following table provides an overview of common upscaling methods:

Conventional upscaling[17]	Class-matching	Derive average SOC stocks per hectare per "class": soil type for which a national map exists, or combination with other spatial covariates, e.g. land use category, climate type, biome, etc. This approach is used in the absence of spatial coordinates of the source data.
	Geomatching	Point locations with spatial referencing are overlaid with GIS layers of important covariates. Upscaling is based on averaged SOC values per mapping unit.
Digital soil mapping[18] (all methods require geomatching)	Data mining	Multiple regression, classification tree, artificial neural network
	Geostatistics	Regression kriging, kriging with external drift
	Knowledge-based systems	Fuzzy inference system, decision tree, Bayesian belief networks

b) Mapping tools and training workshops

For DSM methods, various guidelines and tools exist which can aid mapping[19].

[17] Lettens, S., J. Van Orshoven, B. Van Wesemael and B. Muys (2004). Soil organic and inorganic carbon content of landscape units in Belgium for 1950 – 1970. Soil Use and Management 20: 40-47.
[18] Dobos, E., F. Carré, T. Hengl, H.I. Reuter and G. Tóth (2006). Digital Soil Mapping as a support to production of functional maps. EUR 22123 EN, 68 pp. Office for Official Publications of the European Communities, Luxemburg.
[19] http://esdac.jrc.ec.europa.eu/projects/dsm-digital-soil-mapping

- The International Soil Research and Information Center (ISRIC) has developed the Global Soil Information Facilities (GSIF), a collection of databases, tools and associated cyber infrastructure for automated soil mapping. Recently, GSIF was used to produce soil property maps for Africa at 1 km resolution according to the GlobalSoilMap.net specifications[20]. ISRIC offers training sessions and workshops on DSM practices[21], e.g. for FAO projects such as carbon mapping in Tanzania[22].
- FAO/Global Soil Partnership (Pillar 2, GSP Education platform[23]): several trainings on digital soil mapping were conducted in support of regional soil partnerships. Training materials were prepared and provided through the GSP portal[24].

For this SOC mapping project, FAO will collect requests for training, organize collective workshops and facilitate partnering between experienced and inexperienced institutions.

Specification 4:	Share details about the upscaling approach 1 Upscaling method (description, citation) 2 Input data/covariates, grid, soil maps, etc.

8.4.5 Temporal dimension: use of existing legacy data, baselines, and future updating

The long-term objective of the Global Soil Partnership is to enable global soil monitoring, and ultimately to update the SWRS report. This objective is fully in line with the needs to update sink/source assessments under UNFCCC/IPCC and the monitoring of SDG indicators (which also includes SOC). Therefore, in the design of this new initiative for SOC mapping, the temporal dimension needs to be considered. The UNFCCC has established 1990 as the reference year/baseline.

It is expected that all data used for this SOC mapping will originate from existing national soil profile databases or existing soil carbon maps. Based on experiences from published SOC maps, many countries probably use various national and/or project-related data sources, therefore combining measurements received from different times/intervals. These circumstances make it difficult to determine a clear baseline for the new global SOC map. While in some countries, recent inventories might be available, in others, data are derived from soil mapping programmes which may extend over several decades (especially for large countries). Combinations of project-related and mapping-related data sets are also likely.

Specification 5:	In order to consider the temporal dimension of the SOC map, it is important to share the sampling date as metadata. If the national data situation allows, pre-1990 or post-1990 sub data sets might be defined. However, it will be an important asset of this SOC map to demonstrate the density of existing soil carbon data sets. The more data points are used, the better the reliability and accuracy of the global product. Subsequent steps to improve the temporal dimension, will be considered at a later stage.

[20] http://www.globalsoilmap.net/biblio
[21] http://www.isric.org/services/training-and-education
[22] http://www.isric.org/projects/carbon-mapping-tanzania
[23] http://www.fao.org/global-soil-partnership/pillars-action/2-awareness-raising/en/
[24] http://www.fao.org/global-soil-partnership/resources/dsm-modules-nena/en/

Because the SOC mapping procedures recommended here rely on reproducible methods (spatial modelling), the SOC map could be reproduced with subsets of soil profiles referring to defined time intervals.

8.4.6 Documentation

The source data used and the methodologies for SOC mapping should be well-documented. A template for documentation will be developed and provided separately through the GSP Portal. Specifications 1 to 5 above serve as orientation for the metadata documentation.

8.5 Data security

A GSP-Data Policy (Intellectual Property Rights) is currently being prepared by the Pillar 4 Working Group to ensure that the GSP data sharing principles – as mentioned in the Pillar 4 Plan of Action and Implementation plan – are fully respected. All national data will remain under the ownership of the data providers and shared data will only be used for the global SOC map.

8.6 Data sharing procedure

Data shared by countries will be collected by the GSP Secretariat. The GSP data policy (see Ch. 8.5) will ensure that the national terms of condition are fully respected. The GSP Secretariat will compile a cookbook for SOC mapping, which will be used as training material and technical guidance for SOC mapping. It will also compile the global SOC map. Data can be shared using common GIS formats and metadata should be compiled in an excel file (template will be provided through the cookbook). Details about the process of data sharing, storage and processing will be discussed during the next meeting of the International Soil Information Institutions (INSII) to be held during the last quarter of 2016.

9. Procedures, tasks, roadmap

9.1 Road map for GSP secretariat activities

Process coordination: GSP Secretariat, supported by voluntary members of ITPS and P4WG prepare guideline for SOC mapping	July 2016
Develop GSP Data policy	July–August 2016
Contact GSP national focal points, GSP partners (especially FAO Member countries) inviting them to develop/share their national SOC maps	August-September 2016
Cooperative joint action 1. If needed, revise SOC guideline based on comments by GSP partners 2. Data sharing: partners provide SOC maps to the GSP secretariat 3. GSP secretariat and other voluntary GSP members support national SOC mapping (through capacity development programmes at regional or national levels) 4. Members still lacking capacity may share point SOC measurements with the GSP Secretariat; secretariat organizes GIS-based SOC mapping 5. Continue to organize relevant training where requested	August 2016 – February 2017
Organize INSII meeting	November 2016
IPCC/GSP-ITPS conference to scientifically discuss SOC mapping based on interim results	March 2017
Global SOC mapping: – Compilation of all data for the global assessment – Combined uncertainty assessment	April-November 2017

– Harmonization activities where needed and possible (SOC conversions depending on availability of methods; calculation of stocks: Re-calculation of 0-30 cm depth) – Quality control: Completeness, errors (plausibility), iterations with data providers – Coordinate final cooperative publication	
Documentation of methods/publication/data release	World Soil Day (5 December) 2017

Annex 1: Previous SOC mapping

A1.1 Global SOC estimates and the Harmonized World Soil Database (FAO/IIASA/ISRIC/JRC/CAS 2006)[25]

Overview of global soil C databases: http://esdac.jrc.ec.europa.eu/themes/global-data-other-initiatives

a) Global SOC **Estimates and the Harmonized World Soil Database (HWSD)** (Hiederer and Köchy, 2012)[26]

Content: SOC stocks (t ha^{-1}), topsoil (0 – 30cm) and subsoil (30 – 100cm), a) as raster layer with resolution of 30 arc second (grid size of approx. 1km x 1km) and b) raster layer with resolution of 5 arc minute (grid size of approx. 9km x 9km). This map had different predecessors (see also Henry et al. 2009)

Data source: raster 1km (HWSD)

Restrictions: HWSD builds on soil mapping units; its content is based on the attributes of dominating and associated soil groups depending on the source data (SOTER, national polygon maps, Digital Soil Map of the World). The name of the soil mapping units is based on FAO74/FAO90, later converted to WRB 2006. The analytical method for detecting SOC in the source data sets is unknown, and no harmonization has been applied. BD and stone values are derived from coarse estimates. The authors detected non-plausible data values (especially SOC in organic soils). The density of measured data sets (national data, soil profiles/point measurements), and the quality of the derived estimates (BD, Stones) is unknown. Uncertainties cannot be quantified.

b) UNEP WCMC Updated Global Carbon Map (Scharlemann et al. 2011)[27]

Content: SOC stocks to 1m depth, SOC_{conc}, bulk density from HWSD (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009).

Data source: raster 1km (HWSD), HWSD was adjusted and missing data filled in where possible. It improves an earlier SOC map (IGBP-DIS 2000, used in UNEP-WCMC's Carbon and biodiversity: Kapos et al., 2008).

Restrictions: see under a) above

A1.2 Continental SOC maps based on point measurements

a) Europe: LUCAS-Soil

[25] Harmonized World Soil Database v 1.2: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

[26] Hiederer, R. and M. Köchy (2012) – 79 pp. – EUR 25225 EN – EUR Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print), ISBN 978-92-79-23108-7, doi:10.2788/13267

[27] Scharlemann, J.P.W., R. Hiederer, V. Kapos and C. Ravilious (2011) UNEP WCMC Updated Global Carbon Map. United Nations Environment Programme - World Conservation Monitoring Centre.

SOC concentration (g kg^{-1}) in the top soil (**0–20 cm**) (De Brogniez et al., 2015) [28]

<u>Source:</u> LUCAS soil database (Toth et al., 2013a[29], point data set as input data). Sampled at 15 to 20 cm depth

<u>Approach:</u> Regression kriging; map of the associated uncertainty (standard error of the OC model predictions [g C kg^{-1}])
Data quality was assessed taking into consideration the main climatic zones, regions, land cover classes and management practices (Toth et al., 2013b[30]). It includes 25 European Union Member States (excluded Romania, Bulgaria, Croatia)

<u>Restriction:</u> not validated by countries; organic C content in most organic soils was under-predicted; regarded to represent the uppermost 20-30 cm (IPCC depth is 0-30 cm)

b) Europe: EIONET (national) SOC maps 2010 (Panagos et al. 2013)[31]

- depth range of 0-30cm, mineral soil and organic H horizons
- OC density (t ha^{-1}): N=6 countries provided data with coverage of more than 50% (Bulgaria, Denmark, Italy, Netherlands, Poland, Slovakia)
- gravimetric SOC content (in %)

<u>Approach:</u> Development of European data sets for soil erosion and SOC, based on a programme between the European Soil Data Centre (ESDAC) and the Primary Contact Points (PCPs) of EIONET. Countries were asked to report using a grid of 1km x 1km cells that were assigned to each country. For each cell, countries had to provide their best estimate of SOC content and soil erosion pertaining to that cell. EIONET data providers were also requested to include explicit meta-data that would allow the correct interpretation of the cell values. The information requested in the meta-data include the period of the ground survey(s), the method used for a spatial interpolation of point data and the land use types covered. Less than half of the contacted countries shared data. <u>Data from some countries needed some further processing in order to be able to deliver according to the established protocol</u>.

Other European assessments for spatial soil C stocks using regression kriging have been conducted with data from the ICP Forests (forest SOC stock)[32] and GEMAS (SOC concentration for grassland and cropland)[33].

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[28] De Brogniez, D., C. Ballabio, A. Stevens, R. J. A. Jones, L. Montanarella and B. van Wesemael (2015). A map of the topsoil organic carbon content of Europe generated by a generalized additive model. European Journal of Soil Science. doi: 10.1111/ejss.12193

[29] Tóth, G., Jones, A. and L. Montanarella, eds. (2013a). LUCAS Topsoil Survey. Methodology, data and results. JRC Technical Reports. Luxembourg. Publications Office of the European Union, EUR26102 – Scientific and Technical Research series – ISSN 1831-9424 (online); ISBN 978-92-79-32542-7; doi: 10.2788/97922"

[30] Toth G., Jones A. and L. Montanarella (2013b) The LUCAS topsoil database and derived information on the regional variability of cropland topsoil properties in the European Union. Environmental Monitoring and Assessment, 185 (9), pp. 7409-7425.

[31] Panagos, P., Hiederer, R., Van Liedekerke, M., Bampa, F. (2013) Estimating soil organic carbon in Europe based on data collected through an European network, Ecological Indicators 24, pp. 439-450.

[32] Baritz, R., D. Zirlewagen, R. Jones, D. Arrouays, R. Hiederer, M. Schrumpf and W. Riek (2011). Carbon in European soils. In: Jandl, R., M. Rodeghiero and M. Olsson (eds). Soil carbon in Sensitive European Ecosystems: From Science to Land Management. John Wiley & Sons, Ltd. p 49-84. (ISBN: 9781119970019)

[33] Baritz, R., V. Ernstsen and D. Zirlewagen (2014). Carbon Concentrations in European Agricultural and Grazing Land Soil. In: Reiman et al. (eds.). Chemistry of Europe's agricultural soils. Part B. General Background Information and Further Analysis of the GEMAS Data Set. Geologisches Jahrbuch, Reihe B, Volume B 103. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (Hrsg.). Schweizerbart'sche Verlagsbuchhandlung, Stuttgart. p. 117 – 128 (Chapter 6).

c) Africa: AfSIS

AfSIS: Use of point data sources to produce soil property maps (regression-kriging); organic carbon, pH, sand, silt and clay fractions, coarse fragments, bulk density, cation-exchange capacity, total nitrogen, exchangeable acidity, Al content, and exchangeable bases (Ca, K, Mg, Na): two resp. six standard soil depths, 250 m spatial resolution, whole African continent.

Point data sources (2008–2014): a) Africa Soil Profiles (legacy) database (ISRIC; Leenaars, 2014); b) AfSIS Sentinel Sites (new soil samples) database (Vagen et al., 2010), jointly consisting of ca. 28 thousand sampling locations.

Annex 2: Cookbook for soil organic carbon mapping

This cookbook will contain specific technical guidance about the upscaling of point-level measurements. It is aimed to provide technical support to GIS mappers and modelers. It will be provided as e-learning material accompanying training of national capacities. The cookbook will be provided as a standalone document which will accompany these guidelines.