Space-time mapping of soil organic carbon stocks

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ISRIC - World Soil Information (The Netherlands)
Woods Hole Research Center (USA)
Cornell University (USA)
Vizzuality (Spain)

Phase 2 - ISRIC Product 1

UNCCD-Modified IPCC Tier 1 Approach

Zhanguo Bai, Gerard B.M. Heuvelink, Laura Poggio and Jonathan Sanderman

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Background

There is a need for a global web-based system to inform on the status and trends of soil organic carbon (SOC). This project develops the ‘Soils Revealed’ platform, which enables decision makers, influencers and the general public to navigate through and interact with high-resolution SOC stock time-series maps for the globe. SOC stock and SOC stock change over the recent past are modelled and mapped using the UNCCD-modified IPCC Tier 1 approach. Suggestions for improvement are provided and implemented. Scenarios are developed and applied to predict SOC stock change in the near future. Finally, a space-time machine learning approach will be experimented to assess if such approach is feasible at the global scale, given the limited available ground data.

This report is one of multiple project deliverables and describes the UNCCD-modified IPCC Tier 1 approach.

1. Introduction

Soil organic carbon (SOC) is one of the most important soil components with its capacity to promote plant growth, recycle nutrients to maintain soil quality and fertility, and clean and store freshwater (UNCCD, 2018). Maintaining SOC stock by providing adequate fresh organic matter for decomposition and adequate land management can generate additional benefits through climate change mitigation and biodiversity conservation.

SOC stocks are influenced by land use and land management that impact litter input rates and soil organic matter loss rates. Inputs are primarily controlled by decisions impacting the Net Primary Production and the retention of dead organic matter (e.g., amount of biomass removed from the land and residues left on the land), while outputs are mostly influenced by management decisions that affect microbial and physical decomposition of soil organic matter (e.g., tillage intensity) (IPCC, 2006; IPCC, 2019). Depending on interactions with previous land use, climate and soil properties, changes in management practices may increase or decrease SOC stocks.

To quantify the SOC stock change over time, the Intergovernmental Panel on Climate Change (IPCC) designed three tiered approaches (IPCC, 2006; IPCC, 2019):

- Tier 1 methods are designed to be the simplest to use, for which equations and default parameter values have been developed. It typically makes use of globally available Earth observation data sources.
- Tier 2 uses the same methodological approach as Tier 1 but makes use of country-specific or region-specific data.
- Tier 3 uses higher-order methods, including dynamic models and on-the-ground observations.

The tiered approach enables national authorities to use methods consistent with their capacities, resources and data availability.

The United Nations Convention to Combat Desertification (UNCCD) modified the IPCC Tier 1 approach to support national reporting on SOC stock and SOC stock change, since SOC stock is one of three land degradation neutrality (LDN) indicators. Parties to the UNCCD have agreed to report on SOC stock trends at regular time intervals in Nationally Determined Contributions[1]. The UNCCD-modified IPCC Tier 1 method is documented in Chapter 4 of the UNCCD Good Practice Guidelines (UNCCD, 2018).

In this report we summarise the UNCCD-modified IPCC Tier 1 approach (Section 2) and provide a detailed description of how the approach translates into a concrete workflow with specification of data sources (Section 3). The workflow will be implemented and applied in next steps of the project to derive time series of the 0-30 cm SOC stock for the globe at high spatial resolution.

2. UNCCD-modified IPCC Tier 1 method

The UNCCD-modified IPCC Tier 1 method starts from a baseline year for which a SOC stock map is required. Next it models SOC stock change from the baseline year onward by taking into account three SOC change factors related to land use, management and carbon input.

Baseline SOC stock map

The Tier 1 approach uses ISRIC's SoilGrids250m 0-30cm SOC stock map (Hengl et al., 2017) as a baseline SOC stock map for the year 2000. Although SoilGrids250m was not made specifically to represent SOC in the year 2000 (since it was constructed from legacy soil data spanning multiple decades), it is a high-resolution, globally consistent, and freely accessible product. It was made using reproducible Digital Soil Mapping techniques and calibrated with more than 240,000 soil profile observations and over 150 global environmental covariates. An update of this map will presently be released by ISRIC and used in this project (see Section 3).

Change factors and their effect on SOC stock trends

The UNCCD-modified Tier 1 approach considers three change factors:

1. A **land use factor** (FLU) that reflects carbon stock changes associated with land use change.
2. A **management factor** (FMG) that represents the effect of management practice on SOC stock.
3. An **input factor** (FI) representing the effect of different levels of carbon input to soil on SOC stock.

For global applications there currently are no suitable data sources to assess the FMG and FI factors. Therefore, these are typically set to 1, that is the default value that indicates no

1 https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs

SOC stock change. Assuming land cover can be a stand-in for land use, the FLU change factor can be populated from an indicator for land cover and its transitions over time.

Based on requirements of: 1) global coverage; 2) appropriate spatial resolution; 3) regular temporal coverage; 4) validated product; and 5) immediate availability for use, the UNCCD selected the European Space Agency (ESA) CCI-LC 300m dataset (ESA, 2017) as a default data source for the assessment of land cover in time and space. This dataset provides annual time series of land cover from 1992 until 2018. It distinguishes 36 land cover classes, which were aggregated to 7 land cover classes used by the UNCCD (Table 1 in the Appendix, copied from UNCCD, 2018, Table 1).

A land cover change leads to an increase or decrease of the SOC stock, depending on whether the FLU that is associated with the change is bigger or smaller than 1 (FLU equal 1 indicates no SOC stock change). The FLU change factors for each land cover conversion combination were copied from Table 10 of UNCCD (2018) and are given in Table 2 in the Appendix. Unfortunately the UNCCD table is partially inconsistent and incomplete. We used the coded factors from the Trends.Earth plug-in (Trends.Earth, 2019) to fill gaps or resolve ambiguities.

Some of the FLU change factors depend on climate zone. Therefore, a global climate map is needed to apply the methodology. For this the Global Agro-Ecological Zones (IIASA/FAO, 2012) map is used, which has 12 classes and is assumed constant during the time period considered. The 12 climate classes are not the same as those used in Table 10 of UNCCD (2018). We resolved this problem by using the factors used by the Trends.Earth plug-in, which do refer to the 12 climate classes of the Global Agro-Ecological Zones map (see Section 3 for more details).

The effect of land cover change on the 0-30 cm SOC stock as modelled in the UNCCD-modified IPCC Tier 1 approach is not immediate but may take up to 20 years. For instance, if land cover changes from Grassland to Cropland in the Temperate cold zone, then FLU=0.8 (see Table 2 in the Appendix) and the SOC stock will reduce to 80% of its value at the start of the land cover change. This reduction is not instantaneous but is taken as a linear function that takes 20 years to reach the final state. If the initial SOC stock is 25.0 ton/ha and FLU=0.8, then the annual SOC stock decrease is $(25.0 - 0.8 \times 25.0) / 20 = 0.25$ ton/ha. Thus, after 6 years the SOC stock has reduced to 23.5 ton/ha, and after 20 years to 20.0 ton/ha. However, this assumes that no other land cover change takes place during these 20 years. If, for instance, after 6 years the land cover changes again, this time from Cropland to Tree-covered, then the 20-year SOC change process starts anew with a new FLU change factor value, which in this case is 1.25 (see Table 2 in the Appendix). The initial SOC stock then is 23.5 ton/ha, which linearly increases to 29.4 ton/ha in 20 years time (unless of course during these 20 years yet another land cover change occurs).

3. Workflow and input datasets

The previous section explained the UNCCD-modified IPCC Tier 1 approach and mentioned some of the data sources used. In this section we work out the method in more detail, with the aim to present a comprehensive, unambiguous and reproducible workflow that will be implemented in a next activity of the project.

Figure 1 shows the general workflow. The various boxes shown in this figure are addressed below.

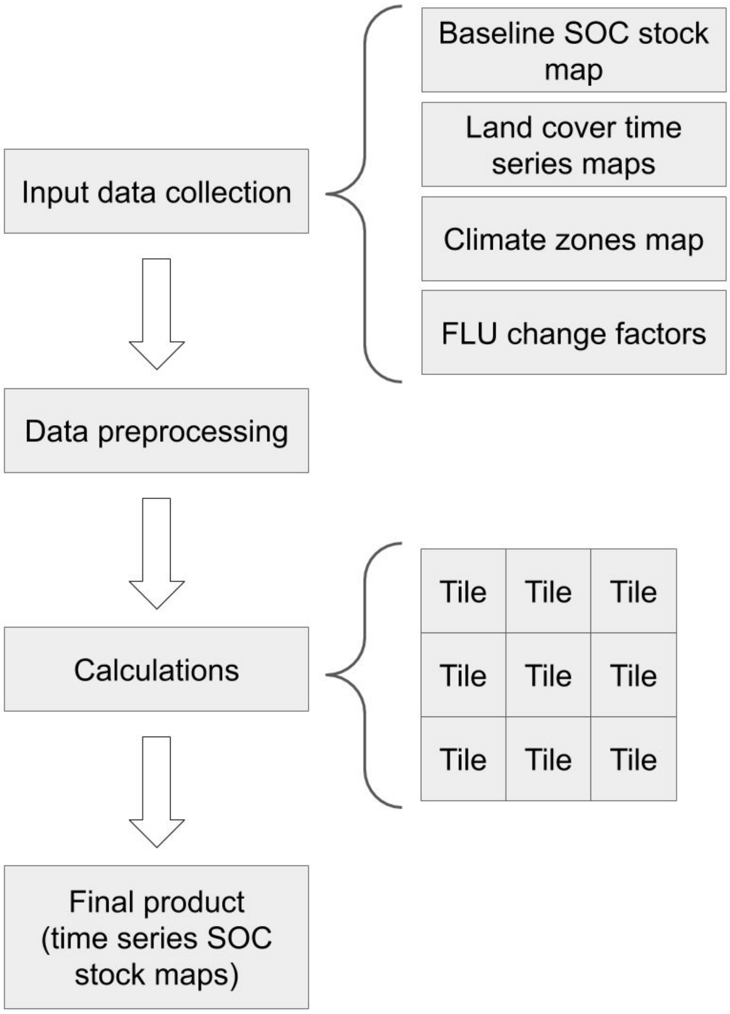

Figure 1. Workflow of the UNCCD-modified IPCC Tier 1 method.

Input data collection

Four inputs are required:

1. We will use the latest available version of SoilGrids250m as a baseline for the **global 0-30 cm SOC stock map**. Small corrections as a response to quality checks of the pre-release[2] of this map are currently being made. In comparison with the 2017 version of this map (Hengl et al., 2017), SOC stock values are lower, while spatial patterns are similar. The map was made using Quantile Regression Forest machine

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2 https://www.isric.org/news/sneak-preview-new-edition-soil-property-estimates-world-and-request-feedback-soilgrids250m

learning and has a spatial resolution of 250m. It uses the Homolosine geographic projection (De Sousa et al., 2019).

2. We will use the **C3S Global Land Cover product**[3] as a source of global land cover from the years 2000 to 2018[4]. Table 1 in the Appendix is used to convert the 36 land cover classes distinguished by this product to the 7 land cover classes used in the UNCCD-modified IPCC Tier 1 method. The C3S Global Land Cover product has a 300 m spatial resolution and a latlon WGS84 geographic projection. We will use version 2.0.7cds for the years 2000-2015 and version 2.2.1 for the years 2016-2018.

3. The **Global Agro-Ecological Zones**[5] from FAO will be used as input for the climatic zones. This map has 12 different climate zones.

4. The **FLU change factors** that we will use are given in Table 2 of the Appendix. These are based on Table 10 of UNCCD (2018), with inconsistencies and incompleteness resolved by checking the implementation in the Trends.Earth plug-in (Trends.Earth, 2019). Most importantly, for FLU change factors associated with conversion from Cropland to Grassland and Tree-covered areas, and vice versa, we used the plug-in to derive factors for each of the 12 climate zones of the FAO map. Note that Table 10 of UNCCD (2017) copied factors from Table 5.5 of IPCC (2006, Chapter 5, page 5.17). Recently, IPCC published refinements to the original change factors (IPCC, 2019, Chapter 5, Table 5.5 on page 5.27). We did not incorporate these because we want to stay as close as possible to the UNCCD implementation.

Data preprocessing

Two main preprocessing steps are required:

1. The ESA land cover dataset will be reclassified according to the UNCCD classification (using Table 1 in the Appendix).

2. The baseline 0-30 cm SOC stock map will be reprojected and resampled to match the 300m land cover map. In this way the least information loss is achieved because the land cover map need not be reprojected and resampled. Note that the land cover map refers to the dominant land cover within a pixel, while the SOC stock map refers to the SOC stock at point locations. The matching of these point values to the land cover grid cells can be done using bilinear interpolation to the centre of the grid cells of the land cover map or by taking the average of all point values within each grid cell. It should be noted that the consequence of working with the latlon WGS84 projection increases calculations by 50%, since this projection is less efficient than the Homolosine projection used by SoilGrids. Thus, if it turns out that calculations are

[3] https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-land-cover?tab=overview
[4] We will extend the time period to 2019 if a land cover map for 2019 is made available before we apply the methodology in Activity 3.
[5] http://www.fao.org/nr/gaez/en

a bottleneck we may decide in a later stage in Activity 3 to take the land cover information loss for granted and do the calculations in the Homolosine projection.

Calculations

Once the baseline SOC stock map and annual land cover maps are prepared and have the same spatial resolution and geographic projection, time series maps of SOC stocks are computed using the land cover maps and FLU change factors.

The calculations are done by one-year increments from the initial year:

1. Initialize the year (i.e., 2000) and define the SOC stock map for the initial year using the SoilGrids SOC stock map. For all grid cells, set the FLU change factor to 1 and ΔSOC to 0.
2. Increase year by 1 and do for every grid cell:
    a. If the latest land cover change was 20 years ago then set FLU to 1 and ΔSOC to 0 (note: in our application this will not occur since our time period is less than 20 years, but it may happen in the scenario runs).
    b. If land cover changed from the previous year to this year then change the FLU factor to the appropriate FLU factor derived from Table 2 in the Appendix and define $\Delta SOC = 0.05 \times (1 - FLU) \times SOC$, where SOC is the SOC stock of the previous year.
    c. Compute SOC stock of this year by subtracting ΔSOC from the SOC stock of the previous year.
3. If current year is 2018 then stop, else go back to step 2.

The processing will be tiled geographically. The size of the tiles will be determined by optimising the balance between computational power and number of files to manage. Computations will be done on the Wageningen University High Performance Computing facility. Computations are expected to be modest in comparison with the computations required for SOC stock change mapping using the machine learning approach (i.e., as used in phase 1 and ISRIC activities 10 to 12 in phase 2 of the project).

Final product

The final output will be global maps of 0-30 cm SOC stock for the years 2000 to 2018 at approximately 300 m spatial resolution. These will be shared with Vizzuality in a jointly agreed projection and format, so that these can be used for publication in the 'Soils Revealed' platform.

Before sharing the maps several quality checks will be done:

1. Check if SOC stock values are returned for the entire global land mask and check that all values are within reasonable bounds.
2. Visual check of spatial patterns and temporal trends.

3. Comparison with outputs of the Trends.Earth plug-in for multiple regions on the globe. Differences should be negligible.

4. Conclusions

The purpose of this first activity in phase 2 of the project was to get a clear understanding of the UNCCD-modified IPCC Tier 1 method and present it in a comprehensive and unambiguous way, to facilitate implementation of the methodology in a next activity. It proved to be more difficult than anticipated because the existing UNCCD and IPCC reports are not in all cases clear, consistent and complete. We therefore also needed to consult the code of the Trends.Earth plug-in on several occasions.

This report may also be useful to initiate the discussion with project partners on how to improve the current methodology (ISRIC activities 4 and 5) and on how to apply and adapt the methodology for future Tier 1 scenarios (WHRC activities 1 to 3). Some options for improvement that may be explored and tested are:

- Update FLU change factors with the refinements published in IPCC (2019).
- Consider whether it is better to let the SOC stock after land cover change converge to a fixed proportion of the current SOC stock or to a pre-determined value that depends on land use, climate, and possibly soil type, management and carbon input.
- Make an explicit distinction between SOC stock change in mineral and organic soils.
- Use an updated climate zone map, such as by applying the IPCC classification methodology (i.e., Figure 3A.5.2 of IPCC (2019)) to WorldClim Version2 global temperature and precipitation maps.
- Investigate if reduction from 36 to 7 land cover classes can be avoided and whether using a more detailed land cover legend leads to improved results.
- Look for ways to include management and, in particular, input change factors for global applications.
- Investigate whether experience with and output of mechanistic SOC stock models (e.g., Gottschalk et al., 2012; Woolf and Lehmann, 2019) may inspire and lead to valuable modifications of the methodology.

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Appendix

Table 1. Land cover class conversion from ESA to UNCCD.

UNCC class	Code UNCCD	CODE ESA	Description
Tree-covered	1	50	Tree cover broadleaved evergreen closed to open (>15%) areas
		60	Tree cover broadleaved deciduous closed to open (>15%)
		61	Tree cover broadleaved deciduous closed (>40%)
		62	Tree cover broadleaved deciduous open (15-40%)
		70	Tree cover needle leaved evergreen closed to open (>15%)
		71	Tree cover needle leaved evergreen closed (>40%)
		72	Tree cover needle leaved evergreen open (15-40%)
		80	Tree cover needle leaved deciduous closed to open (>15%)
		81	Tree cover needle leaved deciduous closed (> 40%)
		82	Tree cover needle leaved deciduous open (15-40%)
		90	Tree cover mixed leaf type (broadleaved and needle leaved)
		100	Mosaic tree and shrub (>50%) / herbaceous cover (< 50%)
Grassland	2	110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)
		120	Shrubland
		121	Shrubland evergreen
		122	Shrubland deciduous
		130	Grassland
		140	Lichen and Mosses
		151	Sparse trees (<15%)
		152	Sparse shrub (<15%)
		153	Sparse herbaceous cover (<15%)
Cropland	3	10	Cropland rainfed
		11	Herbaceous cover
		12	Tree or shrub cover
		20	Cropland irrigated or post-flooding
		30	Mosaic cropland (>50%) / natural vegetation (tree shrub herbaceous cover) (<50%)
		40	Mosaic natural vegetation (tree shrub herbaceous cover) (>50%) / cropland (< 50%)
Wetland	4	160	Tree cover aquatic or regularly flooded in fresh or brackish water
		170	Tree cover aquatic regularly flooded in salt or brackish water Mangroves
		180	Shrub or herbaceous cover flooded fresh/brackish water
Artificial surfaces	5	190	Urban areas
Other land	6	200	Bare areas
		201	Consolidated bare areas
		202	Unconsolidated bare areas
		220	Permanent snow and ice
Water bodies	7	210	Water bodies

Table 2. FLU change factors (adapted from Table 10 in UNCCD (2018) and the Trends.Earth plug-in).

From land cover class	To land cover class	Climate	FLU change factor
Tree-covered, Grassland	Tree-covered, Grassland	All	1.00
Tree-covered, Grassland	Cropland	Tropics warm, Subtropics warm, Subtropics cold, Temperate cool	0.69
	Cropland	Tropics cold, Subtropics cool, Subtropics very cold, Temperate cold	0.80
	Cropland	Temperate very cold	0.64
	Cropland	Boreal cold, Boreal very cold	0.48
	Cropland	Arctic	0.58
Tree-covered, Grassland, Cropland, Artificial Surfaces, Other land, Water bodies	Wetland	All	2.00
Tree-covered, Grassland, Cropland, Other land, Water bodies	Artificial Surfaces	All	0.32
Tree-covered, Grassland, Cropland, Wetland, Artificial Surfaces, Water bodies	Other land	All	0.10
Tree-covered, Grassland, Cropland, Water bodies	Water bodies	All	1.00
Cropland	Cropland	All	1.00
Cropland	Tree-covered, Grassland	Tropics warm, Subtropics warm, Subtropics cold, Temperate cool	1.45
	Tree-covered, Grassland	Tropics cold, Subtropics cool, Subtropics very cold, Temperate cold	1.25
	Tree-covered, Grassland	Temperate very cold	1.50
	Tree-covered, Grassland	Boreal cold, Boreal very cold	2.08
	Tree-covered, Grassland	Arctic	1.72
Wetland	Wetland	All	1.00
Wetland	Tree-covered, Grassland, Cropland, Artificial surfaces, Water bodies	All	0.04
Artificial surfaces	Artificial surfaces	All	1.00
Artificial surfaces, Other land	Tree-covered, Grassland, Cropland, Water bodies	All	2.00
Other land	Other land	All	1.00
Water bodies	Tree-covered, Grassland, Cropland	All	1.00