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Review of existing soil carbon inventories globally, for the tropics, permafrost regions, and wetlands; with an assessment of accuracy

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Abstract

The global soil carbon pool is relevant for the carbon cycle budget. We review current estimates of the global soil carbon mass and carbon masses and stocks in wetlands, tropical and permafrost regions. The Harmonized World Soil Database (HWSD) provides the most recent and coherent global data set for the top 1 m with an amount of 2020 Pg. This number, however, must be corrected for lower bulk density of histosols. Using a medium density of 0.1 kg/dm^3 reduces the amount to 1124 Pg. The Global Lakes and Wetlands Database (GLWD) is the most recent and detailed description of the global distribution of wetlands. Depending on the definition of 'wetland', the carbon mass contained in the top 1 m of wetlands ranges between 94 and 162 Pg. Carbon in soils in the permafrost region amounts to 496 Pg in the top 1 m, 528 Pg in 1 m to 3 m depth, and 648 Pg in depths greater than 3 m. Tropical soils contain 378 Pg organic carbon in the top 1m, including 35 Pg in wetlands according to HWSD and GLWD. About 87 Pg are contained in tropical peatlands (unlimited depth). Assuming that peatlands can be classified as histosols, the total soil mass in the tropics is 442 Pg. Globally, the total organic soil carbon pool is 2588 Pg (excluding soil below 1 m outside tropical peatlands and permafrost region), with 1368 Pg contained in the upper 1 m. Variability in estimates are due to differences in soil unit maps, size of soil property data bases, scarce information about soil carbon at greater depths in peatlands, variation in definitions of soil units and 'peatland'. We present recommendations for improving global soil carbon mapping based on a panel of 15 international soil experts. New global approaches to soil mapping including proximal and remote sensing, digital methods, harmonized soil profile descriptions, and aggregation of existing profile descriptions in a common database require continued support to improve future estimates of the global carbon pool.

Keywords: organic soil carbon, mapping, peatland, permafrost, tropics, carbon cycle

Introduction

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

Soils and biomass represent the large terrestrial carbon stocks. On the short to middle long term, carbon sinks may be explained by changes in biomass, but on longer timescales soil carbon become more relevant. Globally, the largest soil carbon stocks are primarily located in wetlands and peatlands, most of which are located on permafrost and in the tropics. This soil carbon is vulnerable to changes in the hydrological cycle as well as to changes in permafrost dynamics. The total amount of carbon stored in soils and its distribution is still highly uncertain.

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.

Traditionally, the spatial distribution of carbon stocks is 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, land management, vegetation, underlying base material, and soil characteristics measured on representative vertical soil profiles (McBratney et al. 2003). Maps of soil units are linked to their properties. The properties are based on measurements of profiles that have been classified as the same soil unit. Typically measurements on several profiles within the same soil unit have been statistically aggregated (average, median). Missing profile data may be estimated by pedotransfer functions from other physical soil characteristics.

The areal density of organic carbon of a soil layer is determined from measuring the carbon concentration (CC, carbon mass/soil dry mass) and the bulk soil density (BSD) of undisturbed soil samples in homogenous soil layers of thickness d. The areal density is calculated as $CC \cdot BSD \cdot d$. The density is reduced for the volume occupied by gravel, rocks, roots, and ice 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). For calculating the carbon mass for the area of a soil unit, the stock of a soil with unit area (summed over all layers to a standardized depth) is multiplied by the soil unit area.

Concentration: carbon mass/soil dry mass
Content: carbon mass/soil volume = concentration · bulk soil density (BSD)
Areal density of fine soil: carbon mass/soil volume·depth · (1 – rel. volume of rocks, coarse roots, and ice)
Stock: areal density of fine soil integrated over all layers to a specified depth
Mass: stock integrated over a specified area

Lateral variability, temporal variability, and methodological variability (BSD, C concentration, gravel and roots, forms of C, organic layers) contribute to the variability of carbon stock estimates (Ellert et al. 2001).

Here we review existing estimates of soil carbon including their uncertainties and underlying methodologies. We focus on the large C stocks in wetlands, tropical soil, and permafrost at high latitudes.

Global carbon stock

The Harmonized World Soil Database (HWSD, FAO et al. 2009) lists for top (0-30 cm) and subsoil (30-100 cm) C_{org}, BSD, gravel (& CEC, texture) for main and secondary soil types on 30” grid. Derived data at 5’ resolution include O_2 constraint and presence of permafrost (Fischer et al. 2008). Data sources for HWSD are earlier global soil maps published by or in cooperation with FAO, the European Soil Data Base, the Soil Map of China, SOTER regional studies, WISE profile data, WISE pedotransfer and taxotransfer functions. HWSD (v.1.1, 2009) does not yet include the national databases of USA, Canada, Australia. The HWSD is the result of associating existing maps of soil types (if necessary reclassified to FAO standards) with soil characteristics derived from the WISE (v.2) database containing about 9600 soil profiles. The HWSD complements and extends the Digital Soil Map of the World (scale 1:5’000’000 or 5’ resolution, v. 3.6, FAO, 2007) that is widely used. DSMW is the digitized version of the FAO-UNESCO Soil Map of the World (FAO 1971 – 1981) that comprises 106 soil unit classes. The HWSD does not quantify variability or ranges of any soil properties within a soil unit. Its description qualifies that “Reliability of the information contained in the database is variable: the parts of the database that still make use of the Soil Map of the World such as North America, Australia, West Africa and South Asia are considered less reliable, while most of the areas covered by SOTER databases are considered to have the highest reliability (Central and Southern Africa, Latin America and the Caribbean, Central and Eastern Europe).” The range of organic carbon concentrations in HWSD is 0 to 40%. High organic C concentrations are associated with a BSD of 1.1 to 1.4 kg/dm^3, which is more representative of mineral soils, whereas 0.05 to 0.5 kg/dm^3 would be typical of organic soils. Thus, straight estimates of C mass of organic soils based on HWSD data are exaggerated. Therefore, we used a BSD of 0.1 kg/dm^3 for all histosols in HWSD (3.3 Gm^2, cell area multiplied by fraction of histosol). Our value is close to Page et al.’s (2011) best estimate of 0.09 for tropical peatlands, the average value of 0.112 for boreal and subarctic peatland used by Gorham (1991), and the average value of 0.091 kg/dm^3 for Finnish agricultural peat soil (Mäkkilä 1994 in Turunen 2008). Furthermore, we assumed that gravel content was zero where HWSD has no data. We calculated the carbon stock for each soil type within a grid cell and weighted it according to its fraction of the total soil area in each cell. C mass in each cell is the product of C stock and the cell's area assuming an average earth radius of 6371.03 km.

The global organic carbon stock in the top 100 cm is 1124 Tg according to HWSD 1.1 with modified BSD (1098 Pg if the fraction of non-soil area in each pixel is subtracted, 2020 Tg with the original BSD values and full soil cover in each pixel). Further error-checking and gap-filling on the HWSD results in a global C mass in the top 1 m of 1208 Pg (Scharlemann et al.). Henry et al. (2009), using an earlier version of HWSD, reported a mass of 1850 Pg carbon for the top 1 m. Using the Digital Soil Map of the World in conjunction with data derived from the WISE database, Henry et al. (2009) report a global carbon stock of 1589 Pg for the top 1 m and 2521 Pg for the top 2 m. Scharlemann et al. () report a slightly lower mass of 1455 Pg for DSMW and the top 1 m. Soil C mass (0–1 m) based on the IGBP-DIS soil map and WISE (v1) data (2000) is 1494 Pg (Scharlemann et al.). The US Natural Resources and Conservation Services reclassified the FAO–UNESCO Soil Map of the World and combined it with a soil climate map. This map results in a global C mass (0–1 m) of 1376 Pg (Scharlemann et al.).

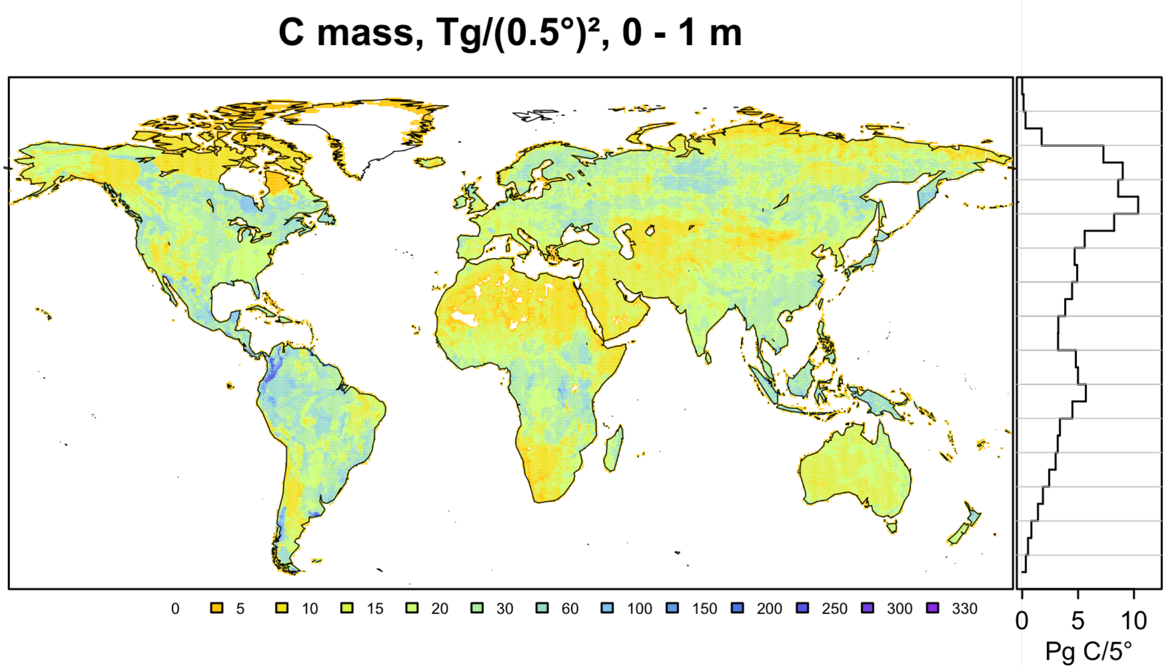


Fig. 1. Global mass of organic carbon in the top 100 cm of the terrestrial soil. Left: per 0.5° pixel, right: per 5° band of latitude. Calculated from modified HWSD v 1.1.

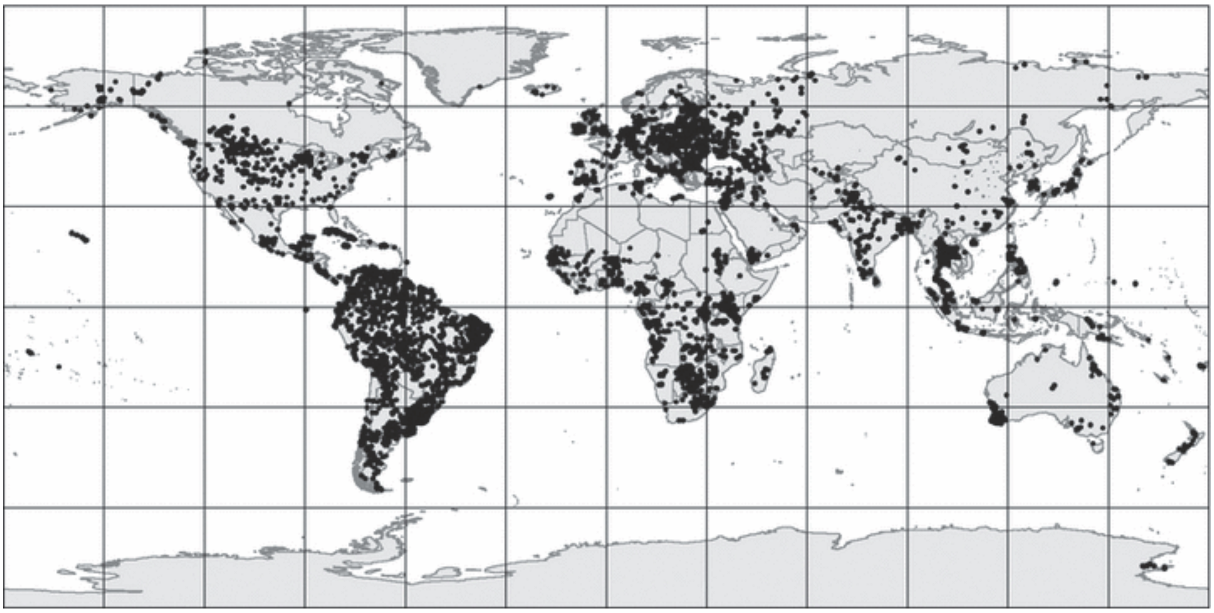
Table 1. Terrestrial soil organic carbon stocks by continent. For the definition of ‘continents’ we used the ESRI (2002) map of continents with coastlines extended by 2 pixels to increase the overlap.

Continent converted to 30” raster	**Carbon stock, 0-1 m (Tg)** modified HWSD 1.1
Asia, incl. Malay Archipelago	391
North America, incl. Greenland, Central America	236
Europe, incl. Iceland, Svalbard, Novaya Zemlya	113
Africa, incl. Madagascar	151
South America	183
Australia, New Zealand, Pacific Islands	47
non-overlapping pixels	3
total (90°N – 60°S)	1124

The World Reference Base Map of World Soil Resources (WRB, IUSS Working Group WRB 2006), scale 1:25’000’000, is generalized from DSMW and includes updates from several databases not yet included in HWSD (v. 1.1). WRB contains 31 dominant soil type classes. Taxotransfer functions must yet be developed to derive organic C stocks from WRB.

The latest ISRIC-WISE database (v.3.1) contains data of more than 10250 soil profiles. The profiles, however, do not yet represent the terrestrial surface equally. Gaps include non-agricultural areas of North America, the Nordic countries, most parts of Asia (notably Iran, Kazakhstan, Russia), Northern Africa, Australia. For calculating soil carbon stocks one needs % C_{org}, BSD, soil depth, gravel. These are provided by 87%, 32%, 100%, 22% (Batjes 2009) of the profiles. Thus, there are at most about two thousand soil profiles available for calculating the global C mass. The temporal origin ranges from 1925 to 2005. The early data may no longer reflect current conditions where C input and decomposition rates are not in balance. Soil properties linked to the DSMW aggregated to various resolutions (0.5°, 5’) are available for WISE v.3 (2005): http://www.isric.org/sites/default/files/private/datasets/WISE30x30min_v3.zip.

SOTER (Worlds Soils and Terrain Database) is an ongoing project to establish a world wide database of soil classes and soil profiles (scale 1:5’000’000) with associated attributes in a standardized format.(http://www.isric.org/projects/soil-and-terrain-database-soter-programme, 20110628). The SOTER database will allow the use of pedotransfer functions instead of taxotransfer functions and thus a more detailed database of soil resources. Maps derived from SOTER are intended to replace HWSD in the long term (http://www.itc.nl/~rossiter/Docs/WRB/SoilMapWorld.pdf).



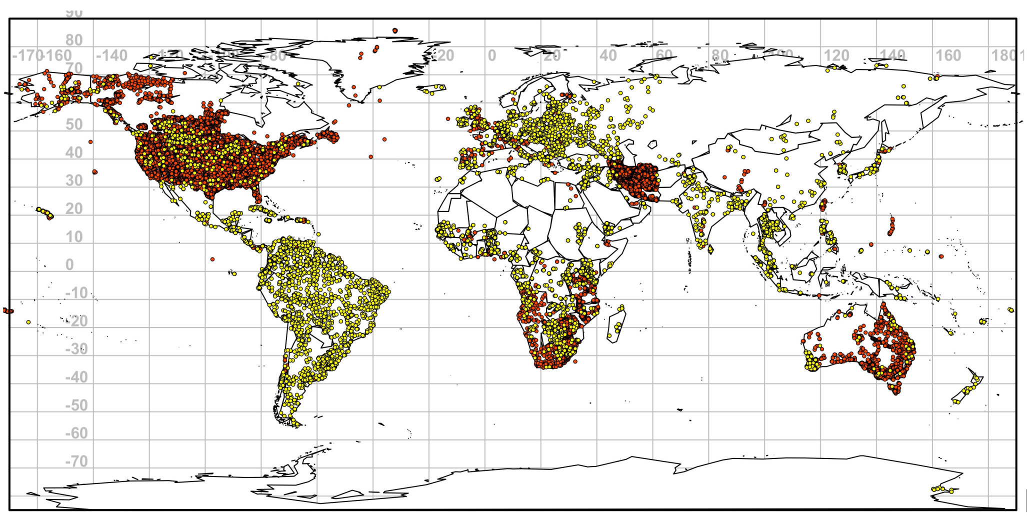


Fig. 2. Origin of soil profile data in WISE 3.1 (Fig. 1 in Batjes 2009).

GlobalSoilMap.net shows the spatial distribution of several existing national and international soil profile datasets, including those not yet in the WISE data base (USDA NCSS Characterization Database, CSIRO National Soil Archive, ISRIC WISE, SPADE, Iran National soil profile database, Canadian Soil Information System, and African soil profiles). The map shows that profiles are scarce in deserts, in North America outside agricultural regions, and in most parts of Asia outside tropical regions and the Middle East. In tropical regions profiles are missing from Brunei, Birma/Myanmar, Bhutan, Laos, Kambodia, Vietnam, North Korea, Liberia, Equatorial Guinea. A German-led project is setting up SOTER databases in Vietnam (https://sfb564.uni-hohenheim.de/83787.html).

Fig. 3. Spatial distribution of several existing national and international soil profile datasets (T. Hengl, 2011-06-16, reproduced* with permission)
*http://www.globalsoilmap.net/system/files/images/Fig_open_soil_profiles_vs.preview.jpg

Frozen high latitude carbon

HWSD (v.1.1) provides information for each soil unit on the presence of a 'gelic phase' indicating the presence of permafrost within the top 200 cm. In addition, the derived supplementary data (Fischer et al. 2008) indicate presence of continuous or discontinuous (i.e., excluding sporadic and isolated) permafrost on a 5' grid. This assessment of permafrost prevalence is based on the analysis of snow-adjusted air frost number (Harrij van Velthuizen, IIASA; pers. comm. 2011) as used for the Global Agro-ecological Zones Assessment v3.0 (Fischer et al., 2011). The extent of permafrost of the supplementary data includes soils (outside the Central Asian mountain ranges) with a gelic phase (Fig. 4). Using the information in the HWSD (v1.1 adjusted), the C mass in the top 1 m of soils with permafrost within the top 200 cm is 177 Pg for 13.5 Gm^2 (Tab. 2). In contrast, within the larger permafrost region outlined by the HWSD supplementary data (17.8 Gm^2), the C mass is 200 Pg. A third, differing permafrost region is described by the Circum-arctic map of permafrost (Heginbottom et al. 1993). Its legend comprises 12 categories of permafrost and ground ice prevalence. The map does not set a depth limit for the occurrence of permafrost and thus comprises 26.3 Pg carbon on 22.9 Gm^2 (including permafrost in the Alps and Central Asian ranges) in the top 1 m. Tarnocai et al. (2009) used the permafrost classification of the 'Circum-arctic map of permafrost and ground ice condition' (excluding the Alps and Central Asian ranges, 18.8 Gm^2) together with carbon and soil information from the Northern Circumpolar Soil Carbon Data Base maintained by Agriculture and Agri-Food Canada (NCSCDB, http://wms1.agr.gc.ca/NortherCircumpolar/northercircumpolar.zip) to estimate organic carbon mass in the permafrost region. This database includes soil profile data not contained in HWSD. Data for calculating organic carbon stocks (C concentration, BSD, depth) in the upper 3 m was derived from 1038 pedons from northern Canada, 131 pedons from Alaska, 253 pedons from Russia, 90 peat cores from western Siberia, 266 mineral and organic soils from the Usa Basin database, and an unquantified number of profiles from the WISE database (version 1.1) for Eurasian soils. Extrapolations were used to estimate C stocks in mineral soils and Eurasian peat soils >1 m depth. The spatial extent of soil classes was obtained from existing digital and paper maps. Tarnocai et al.'s (2009) estimate of 496 Pg for the 0–1 m depth is much higher than that of HWSD. The difference is partly due the limit of 2 m that HWSD uses for distinguishing the 'gelic phase', whereas the Circum-arctic map of permafrost does not refer to a limit (Heginbottom et al. 1993). The more important cause of the difference is the greater C stock calculated from the NCSCDB (Table 2). In NCSCDB the mean C stock of soil in all permafrost classes is >20 kg/m^2, whereas the median C stock is <20 kg/m^2 in HWSD in all regions but the small region with isolated permafrost patches. In addition to the carbon stock in the top 100 cm, Tarnocai et al. (2009) estimated that their permafrost region contains 528 Pg in 1 m to 3 m depth, and 648 Pg in depths greater than 3 m. The accuracy associated with the stocks derives from incomplete knowledge of the spatial distribution of soil classes, soil depths, and sparse distribution of soil profile data. In terms of IPCC A4 categories of confidence, Tarnocai et al. have medium to high confidence (>66%) in the North-American stocks of the top 1 m, medium confidence (33–66%) in the Eurasian stocks of the top 1 m, and very low to low confidence (<33%) in the other stocks. Tarnocai et al. discuss extensively the uncertainty of their estimates. Here we note only that major uncertainty is linked to the area covered by high latitude peatlands (published estimates vary between 1.2 and 2.7 Gm^2) which alone results in a range of 94–215 Pg C. The carbon mass contained in >3 m depth of river deltas is potentially great (241 Pg, Tarnocai et al. 2009), but is based solely on extrapolation on the C stock and area of the Mackenzie River delta. Yedoma (Pleistocene loess deposits with high carbon concentration) carbon mass (407 Pg, >3 m depth) is also associated with great uncertainty. The estimate (adopted from Zimov et al. 2006) is based on a sketched area of 1 Gm^2 in Siberia (thus excluding smaller Yedoma deposits in North America) and mean literature values for depth (25 m) whose ranges extend >±50% of the mean.

Table 2. C stocks (top 1 m) of soils with gelic properties in HWSD v.1.1.

	HWSD		
gelic phase	**area (Gm^2 = 10^6 km^2)**	**C stock (kg/m^2) 5,25,50,75,95% percentile**	**C mass (Pg)**
continuous, >90% of area	5.48	5.9, 7.5, **7.7**, 14.6, 38.0	70
discontinuous, 50-90%	4.14	6.4, 7.1, **9.9**, 19.1, 28.9	56
sporadic, 10-50%	3.81	3.9, 8.7, **12.5**, 15.9, 19.2	48
isolated, 0-10%	0.05	8.4, 28.1, **32.8**, 32.8, 32.8	2
whole area	13.49	5.3, 7.1, **10.3**, 15.9, 32.9	177

Table 3. Comparison of C stocks (top 1 m) between HWSD v.1.1 and NCSCDB (Tarnocai et al. 2009). Permafrost contingency refers to the Circumarctic Permafrost Map.

	HWSD							**NCSDB**		
permafrost contingency of NCSDB	**area (10^6 km^2 = Gm^2)**	**C stock (kg/m^2) 5,25,50,75,95% percentile**					**C mass (Pg)**	**soil area (10^6 km^2 = Gm^2)**	**C stock (kg/m^2), mean**	**C mass (Pg)**
continuous, >90% of area	10.4	4.1	7.1	**8.4**	15.5	20.3	116	10.1	29.5	299
discontinuous, 50-90%	3.1	4.4	7.1	**12.9**	17.8	32.6	43	3.1	21.8	67
sporadic, 10-50%	3	4.9	7.4	**12.7**	18.2	35.7	42	2.6	24.3	63
isolated, 0-10%	3.6	5.4	7.8	**10.3**	17.2	32.6	48	3.0	22.6	67
whole area	20.1	4.4	7.1	**9.6**	15.9	28.4	249	18.8	26.4	496

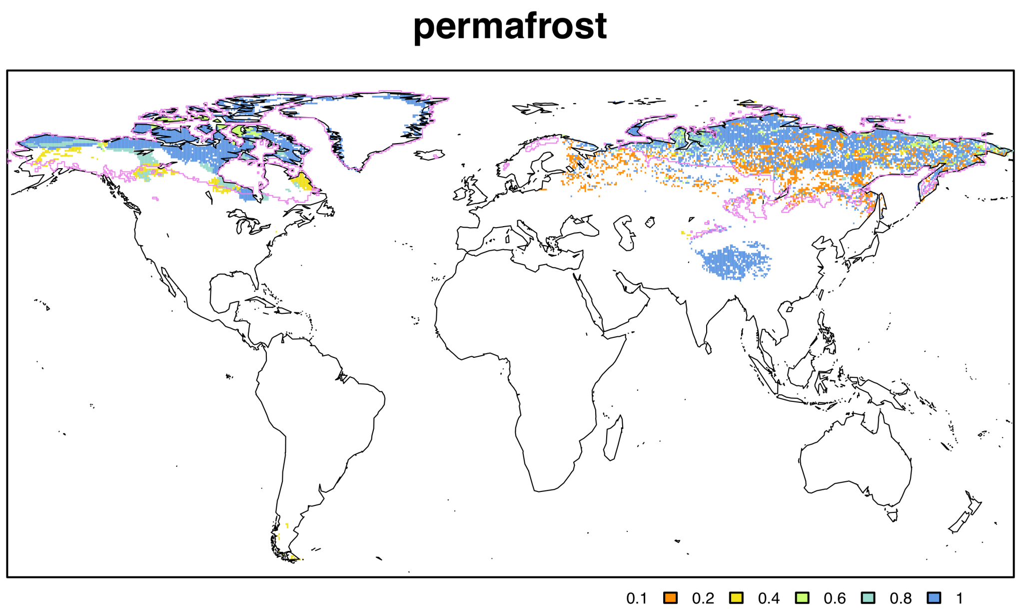


Fig. 4. Extent of permafrost in HWSD v1.1. Colour scale: fraction of soil units within a 30” pixel with ‘gelic phase’ (averaged for display to 30’); pink outline: permafrost attribute in HWSD supplementary data sets SQ1–7 at 5’.

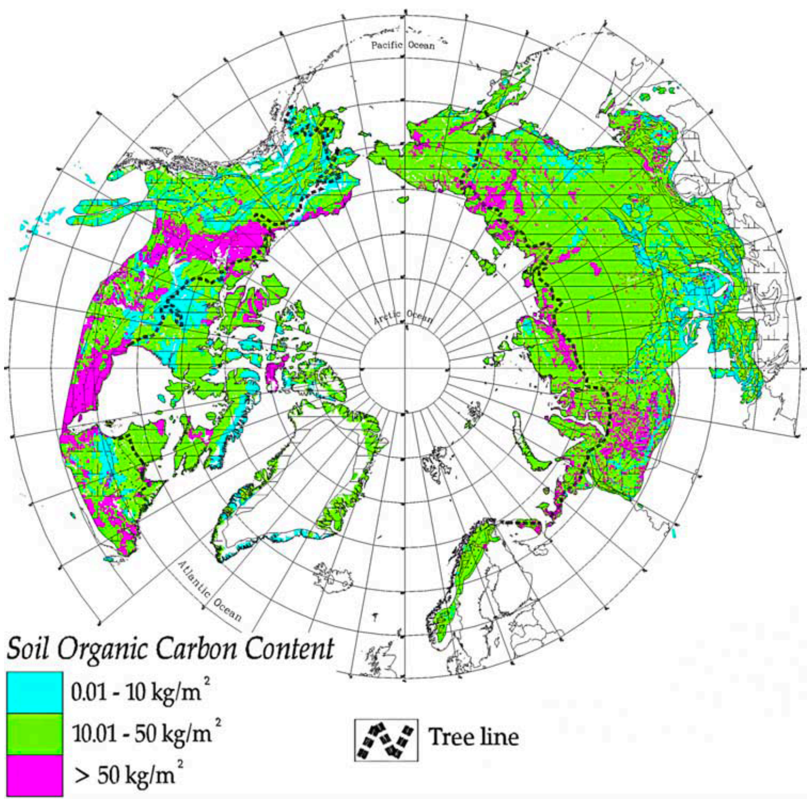


Fig. 5. Soil C in the northern permafrost region. (Fig. 3 of Tarnocai et al. 2009, used with permission by AGU).

Carbon in global wetlands

Carbon stocks in wetlands are in principle great because water reduces the availability of oxygen and thus greatly reduces decomposition rates (Freeman et al. 2001). Draining of wetlands often greatly increases the decomposition of dead plant material and release of carbon dioxide into the atmosphere. This process can significantly affect the global carbon budget when it happens at a large extent. There is, however, no consensus of what constitutes a wetland at the global scale (Mitra et al. 2005). Therefore the volume of wetland soil and its carbon mass are also uncertain (Joosten 2010).

The most detailed and recent maps of global scope are the Global Land Cover Characteristics database, v 2.0 (GLCC, Loveland et al. 2000) that comprises up to 6 wetland types ('Wooded Wet Swamp', 'Rice Paddy and Field', 'Inland Water', 'Mangrove', 'Mire, Bog, Fen', 'Marsh Wetland') and the Global Lakes and Wetland Database (GLWD, Lehner and Döll 2004) that comprises 12 wetland categories. Both maps have a resolution of 30". The Global Land Cover Characterization originates from analysis of remote sensing data in the International Geosphere Biosphere program. Lehner & Döll compiled their data base from existing maps, including the GLCC, and inventories. Due to the heterogeneous classification across the source materials, some wetland categories are restricted geographically. The categories "50-100% wetland" and "25–50% wetland", for example, occur only in North America.

Based on the intersection of GLWD and HWSD (Fig. 6), the global carbon mass in the top 1 m of soil of permanent and non-permanent wetlands (excluding lakes, reservoirs, and rivers) is 162 Tg or 14% of the global mass (Table 3). Using the GLCC Global Ecosystems classification, the area covered by wetlands is much smaller (5 vs 13 Gm^2) and contains only 54 Pg organic carbon (Table 4). The difference is due to the classification of large parts of North America (including the prairie) as temporary or patchy wetland in the GLWD. Even though, the wetlands in a stricter sense in the GLWD cover twice the area and contain nearly twice the mass of carbon of the GLCC wetlands. The contribution of wetlands to the global carbon mass retains a large uncertainty. Wetland classes are defined heterogeneously. The differences in area between GLWD and GLCC indicate that classification of swamp forests, marshes, mangroves, and rice paddies need attention.

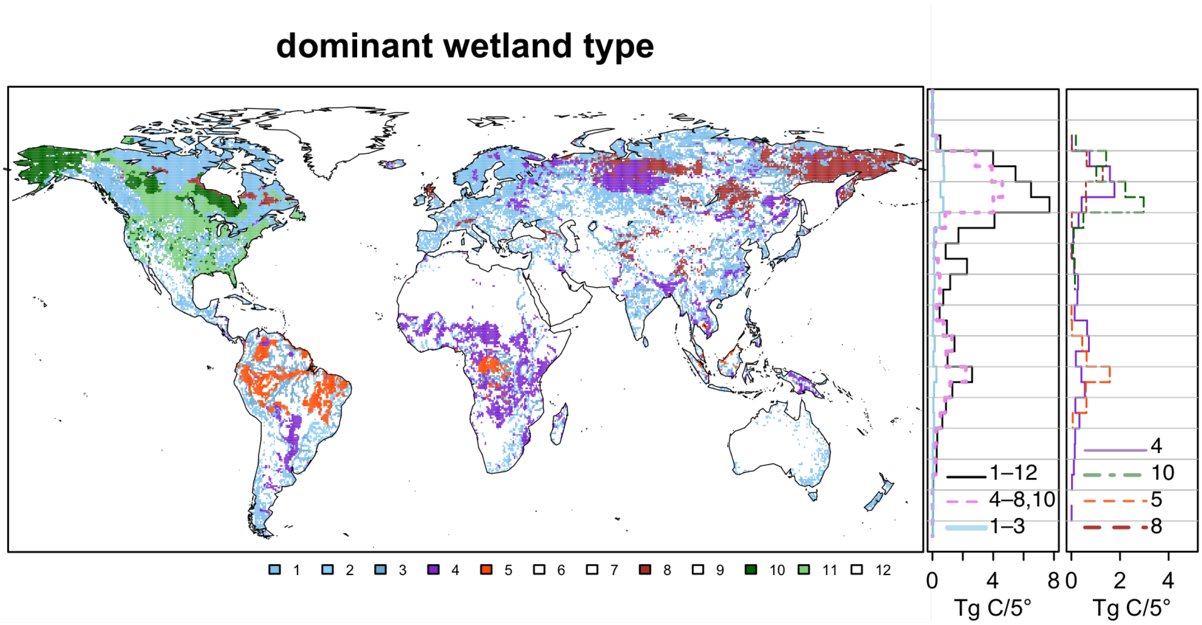


Fig. 6. Left: Global distribution of important wetlands (by carbon mass) according to the Global Lakes and Wetlands Database. The most frequent wetland type is displayed within a 0.5° pixel. Right: Carbon mass in wetland soils (top 1 m) in bands of 5° latitude. For wetland class numbers refer to Table 3.

Table 4. Carbon stocks and masses in the top 1 m of wetland soils derived from the modified HWSD. Wetlands classified according to the Global Lake and Wetlands Database.

Wetland class (GLWD, level 3)	**Area (10⁶ km²)**	**C stock (kg/m²) 5,25,<u>50</u>,75,95 percentile**					**Carbon mass (Pg, 0-1 m)**		
1-3 Lake, Reservoir, River	1.5	4.1	7	**<u>9.2</u>**	15.1	28.1	17.8		
4 Freshwater Marsh, Floodplain	2.4	4.3	7	**<u>10.1</u>**	24.5	38	32.9		
5 Swamp Forest, Flooded Forest	1.2	3.6	5.6	**<u>8.6</u>**	14.4	33.8	13.7		
6 Coastal Wetland	0.4	3.9	6.1	**<u>7.3</u>**	12	27.3	4.4		
7 Pan, Brackish/Saline Wetland	0.4	2.5	3.9	**<u>4.7</u>**	5.4	8	1.6	93.8	
8 Bog, Fen, Mire	0.7	4.4	8.4	**<u>15.5</u>**	20.3	35.6	11.2		144.4
9 Intermittent Wetland/Lake	0.6	2.2	3.5	**<u>4.4</u>**	5.9	9.7	3.1		
10 50-100% Wetland	1.7	7.1	12.5	**<u>13.9</u>**	24.4	38	31.6		
11 25-50% Wetland	3.1	5.6	9	**<u>12.3</u>**	14.9	28	39.2		
12 Wetland Complex (0-25% Wetland)	0.9	5.8	5.9	**<u>5.9</u>**	7.3	12.6	6.7		
Total	12.9	4.1	6.9	**<u>11.3</u>**	17	32.6	162.1		
Dryland	115.2	2.5	4.9	**<u>7.1</u>**	10.6	20.3	961.9		

Table 5. Carbon stocks and masses in the top 1 m of wetland soils derived from the modified HWSD. Wetlands classified according to the Global Land Cover Characteristics Database, Global Ecosystems legend[1].

Wetland class (GLCCD, Global Ecosystems legend)	**Area** (10^6 km²)	**C stock (kg/m²)** 5,25,<u>50</u>,75,95 percentile					**Carbon mass** (Pg, 0-1 m)
13 Wooded Wet Swamp	0.1	3.6	6	**<u>8.7</u>**	12.5	28.4	0.9
14 Inland Water	1.6	4.4	6.9	**<u>9.5</u>**	15.4	28.8	18.1
36 Rice Paddy and Field	2.4	4.8	6	**<u>7.2</u>**	9	12.9	20
44 Mire, Bog, Fen	0.8	4.4	8.4	**<u>15.5</u>**	21.5	38	13.1
45 Marsh Wetland	0.1	5.6	7.1	**<u>15.5</u>**	20.5	32.7	0.9
72 Mangrove	0.0	4.3	6.4	**<u>8.7</u>**	20	23.9	0.5
total	4.9	4.4	6.4	**<u>8.5</u>**	15	29.6	53.6
Dryland	123.2	2.5	5	**<u>7.3</u>**	11.4	21.6	1070.4

Wetlands with the highest carbon concentrations are bogs, fens, mires, and marshes. Due to their high carbon concentration they are also classified as peatland. When wet peatlands are drained they may no longer qualify as wetlands, but remain peatlands with high carbon concentration and large C mass. Drainage exposes the carbon to oxygen and thus accelerates peat decomposition. The global area of peatland with a minimum peat depth of 30 cm is 3.8 Gm^2 based on the International Mire Conservation Group Global Peatland Database (GPD, Joosten 2010). Total carbon mass of peatlands in the GPD is 447 Pg for their total depth. This estimate is considered conservative because mangoves, salt marshes, paddies, paludified forests, cloud forests, dambos, and cryosols were omitted because of lack of data. The information available in the database for peatlands is very heterogeneous. For some countries only the total area of peatland is known. If depth information was missing or not plausible, a depth of 2 m was assumed, although most peatlands are deeper (Joosten 2010). It is not clear, which default values were used for C concentration or bulk density in the assessment. C concentration (ash-free) varies from 0.48–0.52 in *Sphagnum* peat to 0.52–0.59 in *Scheuchzeria* and woody peat (Chambers et al. 2010). Bulk density shows much stronger variation. Ash-free bulk density ranges from $\ll$0.01 to 0.23 in 4697 samples (Chambers et al. 2010) with a median of 0.1 (calculated as the weighted median of medians). The variation is due to water content, soil depth, plant material, and degree of decomposition (Boelter 1968). The highest density is found in well decomposed, deep peat of herbaceous or woody origin at low water content. The great variation commands that bulk density of peatlands be actually measured at several depths and at ambient soil moisture. If this is not possible, pedotransfer functions ought to include water content, decomposition status, and plant material.

Peatlands with a certain thickness of organic layer qualify as histosols. The FAO, for example, defines histosols in the 1974 edition of the FAO-UNESCO Soil Map of the World and in the DSMW as "Soils having an H horizon of 40 cm or more (60 cm or more if the organic material consists mainly of sphagnum or moss or has a bulk density of less than 0.1) either extending down from the surface or taken

[1] GLCCD-Global Ecosystems legend comprises other wetland classes that have zero area: 65–68 Coastal Wetlands, 73 Water and Island Fringe, 74 Land, Water, and Shore, 75 Land and Water, River.

cumulatively within the upper 80 cm of the soil; the thickness of the H horizon may be less when it rests on rocks or on fragmental material of which the interstices are filled with organic matter.” Histosols in HWSD v1.1 are defined according to the FAO-74 legend, an interim FAO-85 legend, or the FA0-90 legend (Revised Legend of the Soil Map of the World). The area covered by histosols in the HWSD, 3.3 Gm^2, slightly lower than the area given by the GPD. The total area of cells with at least some fraction of histosol, however, is 10 Gm^2 with 196 Pg C representing 17% of the global C mass in the upper 1 m. Most of the histosol cell area (6.2 Gm^2) is outside wetlands and contains 116 Pg carbon in the upper 1 m. This indicates that a large portion of originally wet peatland has been drained and is exposed to decomposition.

Wetland category	area, Gm^2 histosol fraction < 0.5	area, Gm^2 histosol fraction ≥ 0.5
GLWD		
1-3 Lake, Reservoir, River	1.480	0.091
4 Freshwater Marsh, Floodplain	2.032	0.389
5 Swamp Forest, Flooded Forest	1.140	0.024
6 Coastal Wetland	0.385	0.009
7 Pan, Brackish/Saline Wetland	0.357	0.000
8 Bog, Fen, Mire	0.602	0.074
9 Intermittent Wetland/Lake	0.630	0.000
10 50-100% Wetland	1.198	0.533
11 25-50% Wetland	2.802	0.306
12 Wetland Complex (0-25% Wetland)	0.883	0.009
GLCC outside GLWD		
13 Wooded Wet Swamp	0.042	0.000
14 Inland Water	0.538	0.016
36 Rice Paddy and Field	2.121	0.003
44 Mire, Bog, Fen	0.042	0.002
45 Marsh Wetland	0.019	0.000
Σ wetland	14.269	1.457
dryland	111.249	1.147

The contrasting land cover classification as shown of GLWD and GLCC could be overcome by a more generic approach of land cover developed within the UN Framework Convention on Climate Change. The harmonized land cover classification system (LCCS) has been developed by FAO and UNEP (di Gregorio and Jansen 2005) and submitted to ISO for incorporation as a standard. The classes are distinguished according to their composition of plant types (mosses/lichens, herbs, woody, with more detailed subclasses), fractional cover, vegetation height, and spatial patchiness. It is suitable for in situ surveys and remote-sensing. Remote sensing methods are developed further on regional scales, e.g. the GlobWetland project (http://www.globwetland.org, see also the special issue in Journal of Environmental Management 90(7)) or the Wetland Map of China (http://www.slrss.cn) (Niu et al. 2009). In situ measurements, however, of soil carbon concentration, soil depth, and bulk soil density, however, must still be improved for calculating soil mass.

Tropical carbon

High intensity of rain in some parts of the tropics explains that 8% of the tropical region (23.5°N–23.5°S) is covered by wetlands containing 32 Pg carbon (Table 5, excluding inland waters). Most of the wetland carbon (25.8 Pg) is found in the categories “Freshwater Marshes, Floodplains”, and “Swamp Forest, Flooded Forest” according to the intersection of HWSD with GLWD. This contrasts strongly with the inventory according to the GLCC. Here, the extent of wetlands is about half that recognized by GLWD and contains only 12 Pg carbon (excluding inland waters) in the top 1 m. The GLCC categories “Wooded Swamp” and “Marsh Wetland”, however, although similar in name to the GLWD categories richest in carbon, contain only 1.1 Pg carbon. On the other hand side, most of the carbon in GLCC categories is contained in “Rice Paddy and Field” (10.4 Pg) of which only 8% are recognized as wetland in GLWD. Thus, the total area of tropical wetland including rice paddies is about 4 Gm^2 containing 40 Pg carbon in the upper 1 m.

Table 6.

Wetland class (GLWD, level 3)	**Area** (10^6 km^2)	**C stock (kg/m^2)** 5,25,<u>50</u>,75,95 percentile					**Carbon mass** (Pg, 0-1 m)		
1–3 Lake, Reservoir, River	0.3	3.9	5.9	**8**	11.5	23.6	3.4		
4 Freshwater Marsh, Floodplain	1.2	3.7	6.1	**7.6**	10.2	23.9	11.9	29.1	32.0
5 Swamp Forest, Flooded Forest	1.2	3.6	5.6	**8.6**	14.4	33.8	13.7		
6 Coastal Wetland	0.3	4	6.1	**8.8**	14.5	28.8	3.4		
7 Pan, Brackish/Saline Wetland	0.1	2.5	3.2	**4.3**	5.3	8	0.5		
8 Bog, Fen, Mire	0	2.5	6	**6**	11.9	12	0		
9 Intermittent Wetland/Lake	0.2	2.2	3.3	**4.1**	5	6.2	0.9		
10 50-100% Wetland	0	0	0	**0**	0	0	0		
11 25-50% Wetland	0	0	0	**0**	0	0	0		
12 Wetland Complex (0-25% Wetland)	0.2	5	5.9	**6.5**	8.2	13.2	1.6		
Total	3.5	3.3	5.6	**7.3**	11	28.4	35.4		
Dryland	44.8	2.2	4.3	**6.2**	8.5	16	342.9		

Wetland class (GLCC, Global Ecosystems legend)	**Area** (10^6 km^2)	**C stock (kg/m^2)** 5,25,<u>50</u>,75,95 percentile					**Carbon mass** (Pg, 0-1 m)
13 Wooded Wet Swamp	0.1	3.7	6	**8.5**	11.6	27.7	0.7
14 Inland Water	0.4	3.9	5.9	**7.9**	10.8	22.9	4.2
36 Rice Paddy and Field	1.2	5.6	6.2	**7.1**	8.8	16	10.4
44 Mire, Bog, Fen	0	2.5	6	**6**	11.9	12	0
45 Marsh Wetland	0	6.1	8.6	**19.7**	24.1	26.1	0.4
72 Mangrove	0	4.3	6.4	**8.7**	20	23.9	0.5
total	1.8	4.7	6.2	**7.2**	9.5	21.7	16.3
Dryland	46.5	2.2	4.3	**6.2**	8.6	16.9	362.0

Less than 20% each of the area in the carbon-richest tropical wetland categories are categorized as histosols in HWSD, totalling 0.4 Gm^2. The mass of carbon in cells with at least some fraction of histosol equals 25 Pg on 1.3 Gm^2. Cells with histosol outside wetlands (GLWD) contain 14 Pg carbon on 0.8 Gm^2. The area of histosol is within the range of the estimated area of tropical peatland (Page et al.). Defining peatland as soil having >65% organic matter in a minimum thickness of 30 cm, Page et al. give a best estimate of tropical peatland area of 0.441 Gm^2 (range 0.387–0.657 Gm^2).

Page et al. (2011) used peatland area, thickness, bulk density and carbon concentration to calculate the carbon mass for each country within the tropics of Cancer and Capricorn. They tried to trace the original data and used best estimates where data were missing. Most data was available for peatland area. Less data was available for peat thickness. Page et al. used 25% of maximum thickness if only this information was reported instead of mean thickness and used 0.5 m if no thickness was reported. Information on BSD and C concentration were rare. When they were provided they often referred only to the subsurface although they vary with depth. If this information was missing, Page et al. used 0.09 g/cm^3 and 56% as best estimates. Their best estimate of carbon mass is 88.6 Pg, with a minimum of 81.7 and a maximum of 91.9 Pg for the whole soil depth. We noted great differences for individual countries between Joosten's (2010) and Page et al.'s (2011) estimates. For example. Joosten's estimate for Sudan is 1.98 Pg, whereas Page et al. have 0.457 Pg. Differences may be caused by different definitions of "peat" and variability in depth estimates, C concentration, and BSD in the data sources.

For estimating total tropical carbon mass, we replace the mass of C in histosol cells (25 Pg) by Page et al.'s best estimate for tropical peatland (88.6 Pg). We note that doing so we neglect carbon below 1 m outside peatlands. Our calculation results in 442 Pg. Thus, peatlands would contain 20% of the tropical soil carbon mass.

Global soil carbon mass — reprise

Assuming that the assessment of Tarnocai et al. of the carbon mass is more accurate than that of HWSD, we update the global soil C mass within the top 1 m to 1368 Pg (496 + 872 Pg). We can use the best estimates of the total C mass for the permafrost region (1672 Pg, Tarnocai et al. 2009) and the tropics (442 Pg, see above) and add it to the C mass outside these areas (474 Pg, HWSD 1.1 adjusted). This sum (2588 Pg) does not yet comprise carbon below 1 m outside the permafrost region and the tropics, which, based on the assessment by Henry et al. (2009) may be in the range of 500–1000 Pg. Thus the total organic carbon in soil may range between 3000 and 3500 Pg.

Even if we restrict the assessment to the top 1 m of soil, the global estimate comes with great uncertainty. Henry et al. (2009) assessed the sources of variation carbon mass estimates for Africa. Variation is caused by different soil unit maps, variation in mean soil unit properties related to the size of the soil property database used and the methods of aggregation and different resolutions of base maps. Total C mass varied by –27/+32% around the mean due the use of different databases with the same map. The variation due to the use of different maps was estimated to be –30/+27%.

Recommendations

An international workshop of 15 soil experts (15-16 July 2011, Leuven, Belgium) addressed uncertainties of global soil carbon maps 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. In the following we summarize the consent of the workshop.

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.**

Current activities in global mapping of soil organic carbon

The concerns that have been raised at the workshop and by reviewers of global, regional, or thematic soil carbon mass, together with the importance of soil carbon for climate has resulted in several initiatives to improve soil mapping. Soil carbon has recently been recognized as an Essential Climate Variable by the Global Climate Observing System (GCOS 2010). At the same time, GCOS calls for the development of "a global database of soil carbon measurements and techniques for extrapolation to global gridded products of soil carbon". In the following we present short descriptions of these projects.

SOTER — "*SOTER aims to establish a World Soils and Terrain Database, at scale 1:5 000 000, containing digitized map units and their attribute data in standardized format. The programme is implemented by FAO, UNEP and ISRIC, under the aegis of the IUSS, in collaboration with a wide range of national soil institutes, since 1986. ISRIC plays a lead role in methodology development and programme implementation. Space Shuttle Radar Topographic Mission (SRTM) digital elevation data are now being used to derive the different landform units and to generate terrain information ...; soil attribute data are largely derived from legacy field data. Ultimately, a global SOTER is to replace the FAO-Unesco Soil Map of the World (SMW), the first internationally accepted inventory of world soil resources. SOTER databases are developed using a uniform methodology, endorsed by FAO, UNEP and IUSS, using standard input software. They are developed at scales ranging from 1:5 million to 1:500 000, depending largely on the needs of the users ….*" (http://www.isric.org/main-themes#Soil%20and%20terrain%20information, viewed 2011-06-27)

Digital Soil Mapping — "*Digital Soil Mapping is the creation and the population of a geographically referenced soil databases generated at a given resolution by using field and laboratory observation methods coupled with environmental data through quantitative relationships. The* [Digital Soil Mapping] *Working Group* *operates under the auspices of the Commissions on Soil Geography (C1.2) and Pedometrics (C1.5) of the International Union of Soil Sciences (IUSS)*" (http://www.digitalsoilmapping.org, viewed 2011-06-27). The Digital Soil Mapping working group initiated the GlobalSoilMap.net project (Sanchez et al. 2009).

GlobalSoilMap.Net — "*A global consortium has been formed that aims to make a new digital soil map of the world using state-of-the-art and emerging technologies for soil mapping and predicting soil properties at fine resolution. This new global soil map will be supplemented by interpretation and functionality options that aim to assist better decisions in a range of global issues like food production and hunger eradication, climate change, and environmental degradation. This is an initiative of the Digital Soil Mapping Working Group of the International Union of Soil Sciences IUSS.*" (http://www.globalsoilmap.net, viewed 2011-06-27). For a detailed account of GlobalSoilMap.net see Hartemink et al. (2010) and http://www.globalsoilmap.net.

Global Soil Partnership — *"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.*

- *Through enhanced and applied knowledge of soil resources as well as improved global governance and standardization, the Partnership will:*
- *Create and promote awareness among decision makers and stakeholders on the key role of soil resources for sustainable land management and sustainable development*
- *Address critical soil issues in relation to food security and climate change adaptation and mitigation*
- *Guide soil knowledge and research through a common global communication platform incorporating real local challenges*
- *Establish an active and effective network for addressing soil crosscutting issues*
- *Develop global governance guidelines aiming to improved soil protection and sustainable soil productivity*" (http://www.fao.org/landandwater/default.html, viewed 2011-06-27)

Open Soil Profiles — An experimental internet platform for submitting soil profile data into a single database, hosted by ISRIC (http://www.soilprofile.org/).

Conclusions

Despite the relevance of soil carbon for CO_2 buffering and climate change, the global mass of soil organic carbon and its distribution remain associated with great uncertainty. Estimates of global and regional soil carbon masses are based on linking soil unit maps with aggregated soil properties for each soil type to calculate carbon stocks. Data on soil properties and soil depth are scarce in regions where carbon stocks are high (peatlands, permafrost) and soil unit maps are less accurate. Furthermore, great parts of Asia outside the tropics lack soil profile descriptions. New global approaches to soil mapping including proximal and remote sensing, digital methods, harmonized soil profile descriptions, and aggregation of existing profile descriptions in a common database require continued support to improve future estimates of the global carbon pool.

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Acronyms

BSD	bulk soil density
DSMW	Digital Soil Map of the World
FAO	United Nations Food and Agriculture Organisation
GLCC	Global Land Cover Characterization Database
GLWD	Global Lakes and Wetland Database
HWSD	Harmonized World Soil Database
ISRIC	International Soil Reference and Information Center
IUSS	International Union of Soil Science
SOTER	World Soil and Terrain Digital Database
WISE	World Inventory of Soil Emission Potentials
WRB	World Reference Base Map of World Soil Resources

Pg	10^{15} g, billion tons
Gm^2	10^6 km^2