Global distribution of soil organic carbon — Part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world

Martin KÖCHY[1,a], Roland HIEDERER[2], Annette FREIBAUER[3]

[1]{Thünen Institute of Climate-Smart Agriculture, Bundesallee 50, 38116 Braunschweig, Germany, Germany}

[2]{Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, 21027 Ispra (VA), Italy}

[3]{Thünen Institute of Climate-Smart Agriculture, Bundesallee 50, 38116 Braunschweig, Germany}

[a]{now at: Thünen Institute of Market Analysis, Bundesallee 50, 38116 Braunschweig, Germany}

Correspondence to: Martin Köchy (office@martinkoechy.de)

Abstract

The global soil organic carbon (SOC) mass is relevant for the carbon cycle budget and thus atmospheric carbon concentrations. We review current estimates of SOC stocks and mass (stock × area) in wetlands, permafrost and tropical regions and the world in the upper 1 m of soil. The Harmonized World Soil Database (HWSD) v.1.2 provides one of the most recent and coherent global data sets of SOC, giving a total mass of 2476 Pg when using the original values for bulk density. Adjusting the HWSD's bulk density of soil high in organic carbon results in a mass of 1230 Pg, and additionally setting the BD of Histosols to 0.1 g cm^{-3} (typical of peat soils) results in a mass of 1062 Pg. The uncertainty of bulk density of Histosols alone introduces a range of –56 to +180 Pg C for the estimate of global SOC mass in the top 1 meter, larger than estimates of global soil respiration. We report the spatial distribution of SOC stocks per 0.5 arc minutes, the areal masses of SOC and the quantiles of SOC stocks by continents, wetland types, and permafrost types. Depending on the definition of 'wetland', wetland soils contain between 82 and 158 Pg SOC. Incorporating more detailed estimates for permafrost from the Northern Circumpolar Soil Carbon Data Base (496 Pg SOC) and tropical peatland carbon, global soils contain 1325 Pg SOC in the upper 1 m including 421 Pg in tropical soils, whereof 40 Pg occur in tropical wetlands. Global SOC amounts to just under 3000 Pg when estimates for deeper soil layers are included. Variability in estimates is due to variation in definitions of soil units, differences in soil property databases, scarcity of information about soil carbon at depths >1 m in peatlands, and variation in definitions of 'peatland'.

1. Introduction

The global mass of soil organic carbon (SOC; for a list of term and acronyms see Table 1) is greater than the combined mass of carbon (C) contained in the atmosphere and in the living biomass (Ciais et al., 2013). Therefore, small relative changes in the mass of SOC can have profound effects on the concentration of atmospheric CO_2 and hence climate change (Myhre et al., 2013). Despite its importance, the global mass of SOC (Scharlemann et al, 2014) and its distribution in space and among land-use/land-cover classes is not well known (Jandl et al., 2014).

On the short to middle term (decades), variation in SOC mass is strongly related to the balance of input from net primary production and microbial decomposition. On longer time-scales, however, changes in the decomposable mass of SOC affect this balance. Globally, the largest SOC stocks are located in wetlands and peatlands, most of which occur in regions of permafrost and in the tropics. Decomposition rates in wetlands and permafrost are low due to low availability of oxygen and low temperatures, respectively. This SOC is vulnerable to changes in the hydrological cycle as well as to changes in permafrost dynamics.

A good knowledge of the global SOC mass and its spatial distribution is necessary for assessing, in an international context, where soils are most vulnerable to C losses or which land use/land cover types might provide the best opportunity for C sequestration to mitigate increases in greenhouse gas concentrations. Since SOC mass is a product of several factors, uncertainty (or errors in measurement) in one of the factors affects all others. Consequently, the measures to reduce the uncertainty of global SOC mass should be directed to those soils that are associated with a large extent (area), high levels of C_{org}, low bulk density (BD) or great depth. Variations at the lower end of BD are more consequential than at the high end of BD because low BD is associated with organic soils (high C_{org}) and a change from, say, 0.1 to

0.2 leads to a doubling of SOC stock and mass. Variation within the range of BD typical of mineral soils, e.g., 1.2 – 1.8 g cm^{-3}, is less consequential.

The spatial distribution of SOC stocks is typically derived from maps (printed or electronic) where areas with similar soil characteristics are aggregated to form soil units, and the SOC mass of the area of the soil unit is calculated by multiplication of the area of the soil unit with its unit-area SOC stock (Amundson, 2001). Historically, soil maps have been compiled largely based on the experience of soil surveyors, taking into account topography, climate, land use history, land management, vegetation, parent material, and soil typical characteristics (McBratney et al., 2003b). The spatial soil units are linked to their defining properties, which are based on measurements of soil profiles or an evaluation by experts. Typically, measurements from several profiles within the same soil unit have been statistically aggregated (e.g., averaged). Missing profile data may be estimated by pedotransfer functions (PTFs) from other measured soil characteristics.

The SOC stock, m_C, of a soil column is calculated by integrating the areal density of SOC over all vertical depth layers (or within a specified depth). The areal density of SOC of a soil layer is determined by measuring the organic carbon concentration (C_{org}) and the BD of undisturbed soil samples in homogenous layers of thickness d (Table 1). The areal density, $C_{org} \times BD \times d$, is reduced by the fractional volume f_G occupied by gravel, rocks, roots, and ice in the soil layer, or $m_C = C_{org} \times BD \times (1 - f_G) \times d$. The SOC mass of the area (A) is the product of the soil unit's area and its SOC density ($A \times m_C$). Lateral variation, temporal variation, and methodological differences in measuring any of the necessary soil characteristics (BD, C_{org}, volume of gravel and roots, forms of C, depth) contribute to the variability of SOC stock and mass estimates (Ellert et al., 2001).

The accuracy of spatially interpolated maps of SOC stocks depends on how well the soil units are represented by soil profiles with complete characteristics. The latest WISE database (v.3.1) contains harmonized data of more than 10250 soil profiles (Batjes, 2009), which, however, underrepresent the the non-agricultural areas of North America, the Nordic countries, most parts of Asia (notably Iran, Kazakhstan, and Russia), Northern Africa, and Australia. To calculate SOC stocks one needs C_{org}, BD, soil depth, and volumetric gravel fraction. These are provided individually by 87%, 32%, 100%, and 22%, respectively, of the profiles (Batjes, 2009). BD and gravel fraction have low representation because they are seldom recorded during routine soil surveys. In numbers, 9970 profile descriptions include C_{org} in at least one layer, but of these only 3655 also include BD. Gravel fraction is explicitly indicated for 1100 of the 3655 profiles but earlier versions of the database could not distinguish between zero and absence of value. BD is included for 806 profiles where $C_{org} >$ 3% and for 74 profiles where $C_{org} >$ 20%. The temporal origin of profile descriptions ranges from 1925 to 2005. The early data may no longer reflect current conditions where C input and decomposition rates may have changed. Efforts to expand the database of data-rich soil profiles and to use pedotransfer instead of taxotransfer functions has been going on since 1986 through the SOTER program (http://www.isric.org/projects/soil-and-terrain-database-soter-programme, accessed 2014-07-07, Nachtergaele, 1999).

In this paper we review estimates of the global SOC mass in the top 1 m of soil derived from spatial databases (maps) and additional sources. First, we compare the Harmonized World Soil Database (HWSD, FAO et al., 2012) to earlier spatial databases. The HWSD was the latest and most detailed inventory at the global scale when this study was begun and is still widely used as an international reference (e.g., Wieder et al., 2014, Yan et al., 2014) Next, we describe the adjustments, especially those of BDs of organic soils (Hiederer & Köchy 2011), that are necessary for calculating the SOC stocks from the HWSD. Based on the adjusted

HWSD, we report area-weighted frequency distributions of SOC stocks in the top 1m of soil, in particular for the large SOC stocks in wetlands, in the tropics, and in frozen soils. Frequency distributions can be used to improve the assessment of accuracy in studies where SOC is an independent variable. Finally, we update the HWSD-derived global SOC mass for the permafrost region and tropical peatlands for the top 1 m and complement it with estimates of SOC below 1 m depth. Our conclusions provide recommendations for improving global soil mapping.

2. Comparison of estimates of global SOC mass among existing spatial databases

Historic estimates of global SOC mass compared among 27 studies range between 504 and 3000 Pg with a median of 1461 Pg (Scharlemann et al., 2014). Here we concentrate on comparisons with the most recent ones.

Before the publication of the HWSD, many global estimates were based on the Digital Soil Map of the World (DSMW) (FAO, 2007) or its precursor, the Soil Map of the World (SMW, FAO, 1997). Batjes (1996), using information from 4353 WISE profiles, reported a range of 1462–1548 Pg for 0–1 m depth and 2376–2456 Pg for 0–2 m depth. Henry *et al*. (2009) report a global SOC mass of 1589 Pg for the top 1 m and 2521 Pg for the top 2 m (using an unspecified WISE version). Hiederer *et al*. (2010) report a slightly lower mass of 1455 Pg for DSMW for the top 1 m.

The International Geosphere Biosphere Program (IGBP) (Global Soil Data Task Group, 2000) produced a map of SOC stock on a 5' by 5' grid derived from the DSMW in conjunction with WISE data (v.1, 1125 profiles). SOC mass (0–1 m) based on the IGBP map is 1550 Pg (calculated as SOC stock × grid cell area).

The US Natural Resources Conservation Services reclassified the SMW at 2' and combined it with a soil climate map (Reich, 2000, data —on a 3' grid—, downloaded from http://spatial-analyst.net/worldmaps/SOC.zip). This map shows the distribution of nine classes of SOC stocks that result in a global SOC mass (0–1 m) of 1463 Pg. Analyzing 2721 soil profiles grouped per biome, Jobbágy & Jackson (2000) estimated that the top 1 m contains 1502 Pg SOC, with 491 Pg in 1-2 m and 351 Pg in 2-3 m depth.

The recently published Global Soil Dataset for Earth System Models (Shangguan et al., 2014) with a resolution of 0.5', combined the DSMW with regional soil maps and global and regional profile databases from several sources beyond those used in the HWSD, including the national databases of the USA, Canada, and Australia. Soil profile data and mapping units were matched in several steps intended to result in the most reliable information. Several harmonization steps are applied to the data to derive amongst others soil carbon concentration, bulk soil density, and gravel content and depth for each soil mapping unit. The global SOC stocks are reported as 1923, 1455 and 720 Pg for the upper 2.3, 1.0, and 0.3 m, respectively.

The HWSD (vers. 1.2, FAO et al., 2012) is one of the most recent and most detailed databases at the global scale and widely used as reference. The HWSD contains for the topsoil (0-30 cm) and the subsoil (30-100 cm) values for C_{org}, BD and gravel content for dominant and secondary soil types on a raster of 0.5 arc minutes (0.5'). Data sources for HWSD are earlier global soil maps that were published by or in cooperation with FAO, the European Soil Database, the Soil Map of China, SOTER regional studies, WISE profile data, and WISE pedotransfer and taxotransfer functions. The HWSD does not yet include the extensive national databases of USA, Canada, and 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, which is the largest number used for a global soil map until 2013.

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 global SOC mass calculated directly from the original HWSD (v.1.2) for the upper 1 m of soil is 2476 Pg. Henry *et al*. (2009), using an unspecified earlier version of HWSD, reported a mass of 1850 Pg for the first meter. These high values are, however, due to inconsistencies, gaps, and inaccuracies in the database (Hiederer & Köchy, 2011). The most consequential of the inaccuracies concerns the BD for soils high in C_{org}. In addressing these issues (see next section), we calculated a global mass of SOC in the top 1 m of soil of 1232 Pg after adjusting the BD of organic soils (SOC > 3%) and 1062 Pg after additionally adjusting the BD of Histosols.

3. Processing and Adjustment of HWSD data for spatial analyses

Our analysis of SOC stocks and masses is based on HWSD vers. 1.1, (FAO et al., 2009) because it was the latest version when this study was begun. Version 1.2 of the HWSD adds two new fields for BD (one for topsoil and one for subsoil) based on the SOTWIS database and addresses minor issues that are listed in detail on the HWSD's web site. Since the resulting differences in global mass between HWSD versions were <0.3% (Table 2), we did not recalculate the other values so that all values reported below are calculated based on version 1.1 of the HWSD and a global mass of 1061 Pg unless explicitly mentioned otherwise.

We calculated the SOC stocks for each soil type (*s*) within a grid cell as the areal density over the thickness of the top and sub soil layer, accounting for the volume occupied by gravel, and weighted it with the soil type's areal fraction in each cell or $m_{C,s} \times A_s/\sum A$. Consequently, SOC mass of each cell is the sum over all soil types of the product of SOC stock of each soil type and the fraction of cell area covered by each soil type or $\sum(m_{C,s} \times A_s/A)$.

Despite the harmonization of spatial and attribute data, the HWSD suffers from some residual inconsistencies in the data reported, gaps in some areas covered and errors in the values reported (Hiederer and Köchy, 2011) that required pre-processing of the data. Here we present a correction of overestimated BD values for Histosols contained in the HWSD that was not specifically addressed by Shangguan et al. (2014), Hiederer & Köchy (2011), or Scharlemann et al. (2014). For each processing step the resulting global SOC mass is used as an indication of the magnitude of the data manipulation (Table 2).

(Step 1) We filled missing data for C_{org} in top (4 cases) and subsoil layers (127 cases) with data from cells characterized as the same soil unit and being closest in distance or most similar in topsoil C_{org}. (2) In a similar way, we additionally filled missing values of BD for mineral soils in 27 cases. (3a) In HWSD v.1.1 high C_{org} values (>20%) are associated with a BD of 1.1 to 1.4 kg/dm^3 although values of 0.05 to 0.3 kg/dm^3 would be typical of organic soils (Boelter, 1968, Page et al., 2011). To address this issue, we set the topsoil BD to –0.31 ln(C_{org} [%])+1.38 (R^2=0.69) and subsoil to –0.32 ln(C_{org} [%])+1.38 (R^2=0.90) for C_{org} > 3% based on an analysis of the SPADE/M2 soil profile database (Hiederer, 2010). This results in a global mass of 1230 Pg C for a soil depth of up to 1 m. (4) The maximum C_{org} of Histosols in the HWSD is 47%, resulting in a BD of 0.19 kg/dm^3 for topsoil and 0.15 kg/dm^3 for subsoil using the mentioned equations. In contrast, the best estimate for the BD for tropical peatlands is 0.09 kg/dm^3 (Page et al., 2011), for boreal and subarctic peatland the average BD is 0.112 kg/dm^3 (Gorham, 1991), and for Finnish agricultural peat soil the average value is 0.091 kg/dm^3 (Mäkkilä, 1994 in Turunen, 2008). Therefore, we finally set BD to 0.1 kg/dm^3 for all Histosols in HWSD. After applying steps 1–4, i.e., the SPADE/M2-based corrections for BD and the modification for Histosols, the global mass of SOC in the upper 1 m of soil is 1061 Pg. (3b) If we had adjusted BD only for Histosols and not the other soils with C_{org} > 3%, the global mass would be 1113 Pg. Hiederer & Köchy (2011) used WISE-based corrections for BD with a threshold of C_{org} > 12% (BD_{top} = –0.285 ln(C_{org} [%])+1.457 and BD_{sub} = –0.291 ln(C_{org} [%])+1.389) that result in a higher a global C mass of 1376 Pg in step 3a but a very similar mass (1062 Pg) after the additional BD correction for histosols in step 4. The processing details for step 1 to 4 are contained in the Supplement.

A default reference soil depth of 100 cm is stipulated in the HWSD for each mapping unit as a concession to harmonization of different soil databases. Only Rendzinas, Rankers, Leptosols, and Lithosols are attributed reference soil depths of 30 cm or 10 cm. For most of the remaining soil units the 25-percentile of lowest recorded depth of profiles in the WISE 3.1 database is equal to or greater than the reference depth, i.e., SOC stock within the top 1 m is not underestimated by using the reference depth. The 25-percentiles of recorded depths of

Calcisols (95 cm, n=218), Cambisols (90 cm, n=1164), Cryosols (80 cm, n=6), Durisols (45 cm, n=1), Podsols (80 cm, n=222), Solonchaks (90 cm, n=165), and Umbrisols (49 cm, n=173) are smaller than the reference depths so that C stocks may be overestimated. The overestimate could be substantial for Cryosols, Podsols, and Umbrisols, which have high C_{org} (median >10%). Even though the true soil depth of Cryosols and Podsols can be expected to be deeper than the recorded depth in the databases, this would be of no consequence for the estimated SOC mass of the top 1 m.

The HWSD database was pre-processed and analyzed with R (R Development Core Team, 2011). We summarized adjusted SOC stocks from HWSD globally and by geographic regions, land cover types, and areas with specific soil characteristics (wetlands, peatlands, permafrost soils). To achieve this we intersected raster maps of SOC with thematic maps in a GIS (GRASS 6.4.2, GRASS Development Team, 2011), calculated SOC mass summed over areas, and determined the 5th, 25th, 50th, 75th, and 95th percentiles of SOC stocks within these areas.

4. Spatial distribution of SOC mass based on the adjusted HWSD

The total SOC mass derived from the unadjusted HWSD v1.2 database and using the SOTWIS BD (when available for a soil mapping unit) is 2476 Pg and 1062 Pg after applying the BD correction as described in the previous paragraph.

4.1. Continental distribution of SOC mass

The distribution of SOC mass by continents (Table 3) follows the pattern of terrestrial ecological zones. A large areal fraction of deserts obviously reduces the continental mean SOC stock, whereas a large fraction of frozen organic soil increases the continental mean SOC stock (Fig. 1).

4.2. Carbon in frozen high-latitude soils

Large SOC deposits exist in the frozen soils of the permafrost region and are vulnerable to the effects of global warming. The mass of these deposits, however, is not well known because the area and the stocks of the permafrost region are uncertain. The uncertainty of the area is characterized by the variation in the delineation and thus extent of the permafrost region among different maps and databases, which is due also to different definitions of "permafrost" and associated concepts.

One permafrost delineation is directly defined by the HWSD. The HWSD lists for each soil unit the presence of permafrost within the top 200 cm (a so-called 'gelic phase'). SOC mass in the top 1 m of soils with a gelic phase is 164 Pg for a 13.1 Mm^2 soil area (Table 4). A second delineation is given by the 'Supplementary data to the HWSD' (Fischer et al., 2008). This database indicates on a 5' grid the presence of continuous or discontinuous (i.e., excluding sporadic and isolated) permafrost that is based on the analysis of the 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., 2008). This extent (19.5 Mm^2 cell area, Fig. 2) encompasses the area of soils with a gelic phase and contains 185 Pg SOC on 16.7 Mm^2 soil area according to the HWSD. A third permafrost delineation (24.9 Mm^2 cell area) is described by the Circum-Arctic Map of Permafrost and Ground Ice Conditions (CAMP, Heginbottom et al., 1993), which comprises 12 categories of permafrost and ground ice prevalence without a defined depth limit for the occurrence of permafrost. The CAMP permafrost region (including permafrost in the Alps and Central Asian ranges) represents 21.7 Mm^2 soil area of the HWSD with 249 Pg SOC in the top 1 m.

4.3. Carbon in global wetlands

SOC stocks in wetlands are considerable 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, which results in the release of carbon dioxide into the atmosphere. This process can significantly affect the global C budget when it happens on a large scale. 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 C mass are also uncertain (Joosten, 2010).

The most detailed and recent maps of global scope with detailed wetland classification (Köchy and Freibauer, 2009) 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 0.5'. The GLCC originates from analysis of remote sensing data in the IGBP. Lehner and Döll compiled their database from existing maps, including the GLCC, and inventories. Some wetland types are restricted geographically due to the heterogeneous classification across the source materials. The categories "50-100% wetland" and "25–50% wetland", for example, occur only in North America, "wetland complex" occurs only in Southeast Asia. One consequence is that the global extent of 'bogs, fens, and mires' in the GLWD, 0.8 Mm^2, is smaller than the Canadian area of peatlands, 1.1 Mm^2 (Tarnocai et al., 2002), which is dominated by bogs and fens.

The spatial overlap of the GLWD and the GLCC categories is rather small (Table 6). Only the "Mire bog, fen" category of the GLCC has been adopted completely by the GLWD (Lehner & Döll, 2004). Even categories with similar names like "Freshwater Marsh" vs. "Marsh Wetland" and "Swamp Forest, Flooded Forest" vs. "Wooded Wet Swamps" show little spatial overlap. Despite the GLWD's overall larger wetland area it does not include the areas identified as "rice paddies" in the GLCC.

Based on the intersection of GLWD and HWSD (Fig. 3), the global SOC mass in the top 1 m of soil of permanent and non-permanent wetlands (excluding lakes, reservoirs, and rivers) is 140 Pg (on 117 Mm^2 soil area). Using the GLCC Global Ecosystems classification, the area covered by wetlands (excluding inland waters) is much smaller (3 vs 12 Mm^2) and contains only 34 Pg SOC (Table 7). The difference is partly due to the classification of large parts of North America (including the prairie) as temporary or patchy wetland in the GLWD; but even wetlands in a stricter sense cover twice the area and contain nearly twice the mass of SOC in the GLWD compared to the GLCC. Therefore, we combined both maps for the assessment of SOC stocks and masses (Table 7).

The differences in SOC mass estimates between the GLWD and the GLCC indicate that wetland types are defined heterogeneously and that especially the classification of swamp forests, marshes, mangroves, and rice paddies needs to be harmonized. The contrasting land cover classification could be overcome by using the more generic land cover classes developed within the UN Framework Convention on Climate Change (di Gregorio and Jansen, 2005). Remote sensing methods are being developed to improve the mapping of wetlands, e.g., the GlobWetland project (http://www.globwetland.org, and Journal of Environmental Management 90, special issue (7)) or the Wetland Map of China (Niu et al., 2009).

4.4. Carbon in tropical wetlands

Soils in the tropical land area (50 Mm^2 within 23.5°N–23.5°S) contain 355 Pg SOC in the top 1 m (Table 8). The high intensity of rain in some parts of the tropics contributes to the presence of wetlands (union of GLWD and GLCC classes as in the previous section) in 9% of the tropical land area (50 Mm^2 within 23.5°N–23.5°S) containing 40 Pg SOC (Table 8, excluding lakes, reservoirs, rivers). Most of the wetland SOC (27 Pg) is found in marshes and floodplains, and swamp or flooded forests. The GLCC category with the highest SOC mass (10 Pg) is "Rice Paddy and Field" (1.2 Mm^2 soil and cell area) but only 14% of this area is recognized as wetland in the GLWD.

5. Discussion of HWSD-based SOC masses

In this section we compare values of SOC masses derived from the adjusted HWSD to those given by other important sources for SOC-rich soils in the permafrost region and in peatlands. The values of the other sources are marked in the text by an asterisk for clarity (e.g. 496 Pg*)

5.1. Carbon in frozen high-latitude soils

The permafrost region can be delineated according to different criteria (see previous section). Tarnocai *et al*. (2009) used the CAMP's permafrost classification (20.5 Mm^2 grid cell area, excluding the Alps and Central Asian ranges) together with SOC and soil information from the Northern Circumpolar Soil Carbon Data Base (NCSCDB, http://wms1.agr.gc.ca/NortherCircumpolar/northercircumpolar.zip) to estimate SOC mass in the permafrost region. The NCSCDB includes soil profile data not incorporated into the HWSD. Data for calculating SOC stocks (C concentration, BD, depth, coarse fragments) in the upper 3 m were 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 unspecified number of profiles from the WISE database (v.1.1) for Eurasian soils. Extrapolations were used to estimate SOC mass 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's mass in the CAMP's permafrost region (233 Pg). The difference is partly due the limit of 2 m that HWSD uses for distinguishing the 'gelic phase', whereas the CAMP does not refer to a depth limit (Heginbottom et al., 1993). The difference in mass is not only due to contrasting definitions and extent but even more so due to the greater SOC stock calculated from the NCSCDB (Table 4). In the NCSCDB the mean SOC areal density of soil in all permafrost classes is >20 kg/m^2, whereas the mean SOC areal density is 11.4 kg/m^2 in the HWSD across all classes. The difference suggests that the BD of frozen organic soil is higher than assumed by us.

Inaccuracies associated with the mass estimates arise from incomplete knowledge of the spatial distribution of soil classes, soil depths, sparse distribution of soil profile data and lack of soil profiles with a full complement of measured data. Tarnocai *et al*. discuss extensively the uncertainty of their estimates. In terms of categories of confidence of the Intergovernmental Panel's on Climate Change Fourth Assessment Report (IPCC AR4), Tarnocai *et al*. have medium to high confidence (>66%) in the values for the North-American stocks of the top 1 m, medium confidence (33–66%) in the values for the Eurasian stocks of the top 1 m, and very low to low confidence (<33%) in the values for the other regional stocks and stocks of layers deeper than 1 m. 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 Mm^2) which alone results in a range of 94–215 Pg SOC. In addition to the SOC mass in the top 1 m, Tarnocai *et al*. (2009) estimated that the permafrost region contains 528 Pg* in 1 m to 3 m depth, and 648 Pg* in depths greater than 3 m. The C 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 SOC stock and area of the Mackenzie River delta. Yedoma (Pleistocene loess deposits with high C_{org}) SOC 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 Mm^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.

5.2. Carbon in peatlands

Wetlands with the highest C_{org} and highest SOC stocks are bogs, fens, mires, and marshes and the “25–50%” and “50–100%” wetlands in boreal North America. The latter two categories represent mostly bogs, fens, and small lakes. Due to their high C_{org} these wetland types can also be classified as peatland.

The global area of peatland with a minimum peat depth of 30 cm is 3.8 Mm^2 based on the International Mire Conservation Group Global Peatland Database (GPD, Joosten, 2010). Total SOC mass of peatlands in the GPD is 447 Pg* for their total depth. This estimate is considered conservative because mangroves, salt marshes, paddies, paludified forests, cloud forests, dambos, and Cryosols were omitted because of lack of data. The information in the GPD is very heterogeneous. Missing data for calculating SOC mass had to be be estimated. For some countries only the total area of peatland was known. When depth information was missing or not plausible, a depth of 2 m was assumed in the GPD, although most peatlands are deeper (Joosten, 2010). It is not clear, which default values were used for C_{org} or BD in the assessment. C content (organic C fraction of ash-free mass) varies from 0.48–0.52 in *Sphagnum* peat to 0.52–0.59 in *Scheuchzeria* and woody peat (Chambers et al., 2010). Values of BD show much stronger variation. Ash-free bulk density ranged from <0.01 to 0.23 kg dm^{-3} in 4697 samples (Chambers et al., 2010) with a median of 0.1 kg dm^{-3}. 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. When wet peatlands are drained, they may no longer qualify as wetlands, but remain peatlands with high C_{org} and a large SOC mass. Drainage exposes the carbon to oxygen and thus accelerates peat decomposition and, depending on circumstances, an increase in BD. The great variation demands that BD of peatlands actually must be measured at several depths and at ambient soil moisture at the same time as the C concentration. If this is not possible, PTFs of BD for peat ought to include water content, decomposition status, and plant material.

Peatlands with a certain thickness of organic layer qualify as Histosols. HWSD adopted the FAO definition "Soils having an H horizon of 40 cm or more of organic soil materials (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 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." (FAO, 1997). The area covered by Histosols in the HWSD (Fig. 4) is 3.3 Mm^2 (cell area multiplied by fraction of Histosol), slightly lower than the area given by the GPD, and contains 113 Pg SOC. The total area of cells with at least some fraction of Histosol, however, is 10 Mm^2 containing 188 Pg SOC. The area of Histosol outside wetlands (1.7 Mm^2) might indicate that a large portion of originally wet peatland has been drained and is exposed to decomposition.

5.3. Carbon in tropical peatlands

Six percent of the area of each of the two C-richest tropical wetland types are categorized as Histosols in the HWSD, totaling only 0.1 Mm^2. Including non-wetlands, the total area of Histosols in the HWSD, 0.4 Mm^2, agrees well with the most recent and detailed, independent estimate of tropical peatland area (Page et al., 2011, defining peatland as soil having >65% organic matter in a minimum thickness of 30 cm). The total mass of SOC in grid cells of the spatial layer with at least some fraction of Histosol is 24.2 Pg.

Page *et al*. (2011) used peatland area, thickness, BD and C_{org} to calculate the SOC 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 area, but less data was available for thickness. Page *et al*. (2011) used 25% of maximum thickness when only this information was reported instead of mean thickness and used 0.5 m when no thickness was reported. The percentiles of the frequency distribution of their best estimate of thickness weighted by their best estimate of area per country is 0-10%: 0.5 m, 25%: 1.75 m, 50%-90%: 5.5 m, 97.5%: 7.0 m, mean: 4.0 m ± 2.2 m SD. This distribution can be used for estimates of SOC mass and associated uncertainty in other tropical peatlands. Data on BD and SOC concentration were rare. When they were provided they often referred only to the subsurface, although these parameters vary with depth. When these data were missing, Page *et al*. (2011) used 0.09 g cm^{-3} and 56% as best estimates based on literature reviews. The best estimate of SOC mass for tropical peatlands of Page et al. (2011) is 88.6 Pg* for the whole soil depth, with a minimum of 81.7 and a maximum of 91.9 Pg*. If one assumes an average peat thickness of 4 m and uniform vertical mass distribution, the top 1 m contains 22 Pg* of SOC, close to our HWSD-based estimate for grid cells containing Histosol (24 Pg). Thus, peatlands may contain about 6% of the tropical SOC mass within the first meter and approximately 21% of the total tropical SOC mass (without depth limit). Obviously, the uncertainty of these estimates is great.

Joosten (2010) estimated SOC mass for individual tropical countries based on the Global Peatland Database. For some countries the difference between Joosten's and Page *et al*.'s estimates are large. For example, Joosten's estimate for Sudan is 1.98 Pg*, whereas Page *et al*. have 0.457 Pg*. These differences may be caused by different definitions of "peat" and variability in depth estimates, SOC concentration, and BD in the data sources.

6. Conclusions

6.1. Global carbon mass — reprise

The estimate of the global SOC mass within the top 1 m based on the HWSD (1062 Pg) can be improved if and where other sources provide better estimates. The HWSD estimate of SOC mass for tropical peatlands agreed well with other sources. The SOC mass in the permafrost region estimated by Tarnocai *et al*. (2009) appears to be more accurate than that of HWSD. Therefore, we substitute for the permafrost region the HWSD-based estimate (– 233 Pg [Table 4]) by Tarnocai *et al*.'s estimate (+ 496 Pg). This calculation (1062 –233 + 496 Pg) updates the global SOC mass within the top 1 m to 1325 Pg.

For including deeper soils in an estimate of the global SOC mass, we consider first estimates of deeper soil layers for the permafrost region and tropical peatlands. The best estimate of the SOC mass below 1 m for the permafrost region known to us is 1176 Pg (calculated from Tarnocai et al., 2009). In order to estimate the mass for 1–4 m depth of tropical peatlands, we use 3/4 of Page *et al*.'s best estimate for the top 4 m (66.5 Pg). Additional 389 Pg SOC is contained below 1 m outside the permafrost region and the tropics (Jobbágy and Jackson, 2000). In total, the mass of SOC in the soil is about 3000 Pg, but large uncertainties remain, especially for depths >1 m.

Another source of uncertainty is the estimation of BD. The BD of peat varies between 0.05 and 0.26 kg/dm^3 (Boelter, 1968). If the same range holds for Histosols (3.3 Mm^2 Histosol area, 1 m depth, 34% C_{org}), this variation alone introduces an uncertainty range of –56 to +180 Pg for the estimate of global SOC in the top meter, which is larger than the estimated annual global soil respiration (79.3–81.8 Pg C, Raich et al., 2002). The areal extent of organic soils, their depth, and the BD at different depths should therefore receive the greatest focus of future soil mapping activities.

Soil monitoring is crucial for detecting changes in SOC stocks and as a reference for projecting changes in the global carbon pool using models (Wei et al., 2014, Wieder et al., 2014, Yan et al., 2014). The following conclusions from our study and a workshop of soil experts (Köchy and Freibauer, 2011) with respect to improved soil monitoring agree with more comprehensive recommendations by an international group of experts (Jandl et al., 2014). In situ measurements of soil C_{org}, soil depth, and BD must still be improved, collected, and made available for calculating global SOC mass. Extra care is necessary to reduce variability of data because variability reduces the potential of detecting change. Classification of soils as it is currently used in mapping produces uncertainty in the reported C stock when the characteristics of soil classes are aggregated and then used in further calculations. The use of pedotransfer rules and functions further increases the uncertainty of the real values. Since PTFs 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. For purposes of detecting actual change in C stocks their uncertainty should be quantified. Of course it would be best if C_{org}, BD, and coarse fragments were measured at the same point or sample to reduce effects of spatial variability. Predictive mapping techniques, including geo-statistics, modelling, and other quantitative methods (McBratney et al., 2003a, Grunwald et al., 2011), especially in conjunction with proximal (radiometry, NIR spectroscopy) or hyperspectral remote-sensing of soil properties (Gomez et al., 2008, Stockmann et al., 2015) can potentially reduce uncertainties in SOC mapping introduced by soil classification and help in interpreting spatio-temporal patterns. Whether soils are mapped in the classical way or by predictive methods, mapping of soils should be coordinated with the direct or indirect mapping of SOC input and its controlling factors (land use, land cover, crop type, land use history and land management) and extent and soil depth of wetlands, peatlands, and permafrost.

Uncertainty of SOC stocks in current maps could further be reduced if all soil types and regions were well represented by soil profile data with rich soil characteristics. 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 protection issues, or because they are only known to a very limited number of soil scientists. Existing approaches such as the NCSCB, the GlobalSoilMap.net project, and the Global Soil Partnership (coordinated by FAO), are important steps to improve the situation. These activities would benefit further if all publicly funded, existing soil profile data were made publicly available to the greatest possible extent.

Another source of uncertainty is introduced because profile data and soil maps have been generated by a multitude of methods. Furthermore, if different methods are preferably used for particular soil types or regions, small differences multiplied by large areas can result in significant differences at the global level. Therefore, international activities to harmonize methods of sampling, calculation, and scaling should be supported. The harmonized methods should then actually be applied in soil sampling. Preferably, samples should be archived so that soils can be reanalyzed with improved or new methods or for checking data by more than one laboratory.

6.2. Implications

The strong effect of BD values on the calculation of SOC stocks and regional or global masses should guide the focus of global observation networks to improve not only the observation of SOC concentrations but also on BD. Furthermore, our study describes for the first time the frequency distribution of SOC stocks within broad classes of land-use/land-cover and C-rich environments based on one of the most exhaustive, harmonized, spatially explicit global databases available to date. The frequency distribution allows a more focused spatial extrapolation and assessment of accuracy in studies where SOC is used as an independent variable (e.g., Pregitzer and Euskirchen, 2004). The frequency distributions also provide a foundation for targeting SOC conservation measures (Powlson et al., 2011) and for improving carbon accounting methods with associated uncertainties as used in the UNFCCC (García-Oliva and Masera, 2004).

CO_2 emissions from soils are used in calculations of the global carbon cycle. Direct observations of CO_2 emissions from soils (e.g., by eddy-flux towers), however, cannot be implemented in a spatially contiguous way. Indirect measurements by remote sensing can improve the spatial coverage but require ground observations for conversion from observed radiation to loss of CO_2 from soils and distinction from other CO_2 sources (Ciais et al., 2010). At the global scale, in-situ measurements must be complemented by modelling activities, which are greatly improved if variation in key factors like SOC can be accounted for. Thus, more detailed information on the global distribution of SOC, horizontally and vertically, including accounts of its accuracy and its variability, are necessary to improve estimates of the global carbon flow.

Author contributions

MK designed and carried out the analyses and wrote the manuscript, RH contributed a thorough analysis of inconsistencies in the HWSD and alternative estimates, AF suggested the topic and provided valuable insights on the presentation of the data.

Acknowledgments. We thank Charles Tarnocai for comments on the manuscript. We appreciate the constructive comments of the reviewers. MK was funded by EU FP7 project COCOS (grant 212196) and FACCE MACSUR (BMBF grant 031A103A).

References

Amundson, R.: The carbon budget in soils, Annual Review of Earth and Planetary Sciences, 29, 535-562, doi:10.1146/annurev.earth.29.1.535, 2001.

Batjes, N. H.: Total carbon and nitrogen in the soils of the world, European Journal of Soil Science, 47, 151-163, doi:10.1111/j.1365-2389.1996.tb01386.x, 1996.

Batjes, N. H.: Harmonized soil profile data for applications at global and continental scales: updates to the WISE database, Soil Use and Management, 25, 124-127, doi:10.1111/j.1475-2743.2009.00202.x, 2009.

Boelter, D. H.: Important physical properties of peat materials, Proceedings of the Third International Peat Congress, Ottawa, Ontario, Canada, 18–23 August 1968, Canada. Dept. of Energy, Mines and Resources and National Research Council of Canada, 1968.

Carré, F., R. Hiederer, V. Blujdea, and R. Koeble: Background guide for the calculation of land carbon stocks in the biofuels sustainability scheme drawing on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, JRC Scientific and Technical Reports, EUR 24573 EN, Office for Official Publications of the European Communities, Luxembourg, Office for Official Publications of the European Communities, available at: http://eusoils.jrc.ec.europa.eu/ESDB_Archive/eusoils_docs/other/EUR24573.pdf, 2010.

Chambers, F. M., Beilman, D. W., and Yu, Z.: Methods for determining peat humification and for quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics, Mires and Peat, 7, 7.1-7.10, 2010/2011.

Ciais, P., A. J. Dolman, R. Dargaville, L. Barrie, A. Bombelli, J. Butler, P. Canadell, and T. Moriyama: GEO Carbon Strategy, GEO Secretariat and FAO, Geneva and Rome, GEO Secretariat and FAO, available at: http://www.earthobservations.org/documents/sbas/cl/201006_geo_carbon_strategy_report.pdf, 2010.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R. B. Myneni, S. Piao, and P. Thornton: Carbon and other biogeochemical cycles, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (Eds), Cambridge University Press, Cambridge, UK, and New York, NY, U.S.A., 465–570, doi: 0.1017/CBO9781107415324.015., 2013.

Digital Soil Map of the World, Rome, Italy, available at: http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116, 2007.

Ellert, B. H., H. H. Janzen, and B. G. McConkey: Measuring and comparing soil carbon storage, in: Assessment methods for soil carbon, Advances in Soil Science, Lal, R., J. M. Follett, and B. A. Stewart (Eds), Lewis, Boca Raton, Florida, 131-146, 2001.

ESRI (Environmental Systems Research Institute): World Continents, ESRI Data & Maps 2002, CD 1, Environmental Systems Research Institute, Inc. (ESRI), Redlands, California, U.S.A., 2002.

FAO: FAO/Unesco Soil Map of the World, Revised Legend, with corrections and updates. Originally published in 1988 as World Soil Resources Report 60, FAO, Rome. Reprinted with updates, Technical Paper, 20, ISRIC, Wageningen, ISRIC, available at: http://library.wur.nl/isric/fulltext/isricu_i9264_001.pdf, 1997.

FAO, IIASA, ISRIC, ISSCAS, and JRC: Harmonized World Soil Database (version 1.1), FAO and IIASA, Rome, Italy, and Laxenburg, Austria, 2009.

FAO, IIASA, ISRIC, ISSCAS, and JRC: Harmonized World Soil Database (version 1.2), FAO and IIASA, Rome, Italy, and Laxenburg, Austria, 2012.

Fischer, G., F. Nachtergaele, S. Prieler, H. T. van Velthuizen, L. Verelst, and D. Wiberg: Global agro-ecological zones assessment for agriculture (GAEZ 2008), IIASA, Laxenburg, Austria and FAO, Rome, Italy., IIASA, Laxenburg, Austria and FAO, Rome, Italy., available at: http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/SoilQualityData.html?sb=11, 2008.

Freeman, C., Ostle, N., and Kang, H.: An enzymic 'latch' on a global carbon store, Nature, 409, 149, doi:10.1038/35051650, 2001.

García-Oliva, F., and Masera, O. R.: Assessment and Measurement Issues Related to Soil Carbon Sequestration in Land-Use, Land-Use Change, and Forestry (LULUCF) Projects under the Kyoto Protocol, Clim. Change, 65, 347-364, doi:10.1023/B:CLIM.0000038211.84327.d9, 2004.

Global Soil Data Task Group: Global Soil Data Products CD-ROM (IGBP-DIS), Available from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. [http://www.daac.ornl.gov], 2000.

Gomez, C., Viscarra, R., Raphael A., and McBratney, A. B.: Soil organic carbon prediction by hyperspectral remote sensing and field vis-NIR spectroscopy: An Australian case study, Geoderma, 146, 403-411, doi:10.1016/j.geoderma.2008.06.011, 2008.

Gorham, E.: Northern peatlands: role in the carbon cycle and probable responses to climatic warming, Ecol. Appl., 1, 182-195, doi:10.2307/1941811, 1991.

GRASS Development Team: Geographic Resources Analysis Support System (GRASS) Software, Version 6.4.2, Open Source Geospatial Foundation, http://grass.osgeo.org, 2011.

di Gregorio, A., and L. J. M. Jansen: Land cover classification system (LCCS). Classification concepts and user manual. Software version (2), Food and Agriculture Organization, Rome, Italy, Food and Agriculture Organization, available at: http://www.fao.org/docrep/008/y7220e/y7220e00.htm#Contents, 2005.

Grunwald, S., Thompson, J. A., and Boettinger, J. L.: Digital soil mapping and modeling at continental scales: finding solutions for global issues, Soil Sci. Soc. Am. J., 75, 1201-1213, doi:10.2136/sssaj2011.0025, 2011.

Heginbottom, J. A., J. F. Brown, E. S. Melnikov, and O. J. Ferrians: Circum-arctic map of permafrost and ground ice conditions, Proceedings of the Sixth International Conference on Permafrost, Wushan, Guangzhou, China, 2, 1132-1136, South China University Press, 1993.

Henry, M., Valentini, R., and Bernoux, M.: Soil carbon stocks in ecoregions of Africa, Biogeosciences Discussions, 6, 797-823, doi:10.5194/bgd-6-797-2009, 2009.

Hiederer, R.: Data update and model revision for soil profile analytical database of Europe of measured parameters (SPADE/M2), JRC Scientific and Technical Reports, EUR 24333 EN,

Office for Official Publications of the European Communities, Luxembourg, Office for Official Publications of the European Communities, doi:10.2788/85262, 2010.
Hiederer, R., and M. Köchy: Global soil organic carbon estimates and the Harmonized World Soil Database, JRC Scientific and Technical Reports, 68528/EUR 25225 EN, Joint Research Centre, Ispra, Italy, Joint Research Centre, doi:10.2788/13267, 2011.
Hiederer, R., F. Ramos, C. Capitani, R. Koeble, V. Blujdea, O. Gomez, D. Mulligan, and L. Marelli: Biofuels: a new methodology to estimate GHG emissions from global land use change, JRC Scientific and Technical Reports, EUR 24483 EN, Office for Official Publications of the European Communities, Luxembourg, Office for Official Publications of the European Communities, doi:10.2788/48910, 2010.
IUSS Working Group WRB: World reference base for soil resources 2006. A framework for international classification, correlation and communication, World Soil Resources Reports, 103, Food and Agricultre Organization of the United Nations, Rome, 2006.
Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M. F., Bampa, F., van Wesemael, B., Harrison, R., B., Guerrini, I. A., Richter, D. d., Jr., Rustad, L., Lorenz, K., Chabbi, A., and Miglietta, F.: Current status, uncertainty and future needs in soil organic carbon monitoring, Science of the Total Environment, 468, 376-383, doi:10.1016/j.scitotenv.2013.08.026, 2014.
Jobbágy, E. G., and Jackson, R. B.: The vertical distribution of soil organic carbon and its relation to climate and vegetation, Ecol. Appl., 10, 423-436, doi:10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2, 2000.
Joosten, H.: The global peatland CO_2 picture. Peatland status and emissions in all countries of the world, Wetlands International, Ede, 2010.
Köchy, M., and A. Freibauer: Global spatial distribution of wetlands, COCOS Report, D4.3a, Johann Heinrich von Thünen-Institut, Braunschweig, Germany, available at: http://www.cocos-carbon.org/docs/D4.3a_wetlands_report.pdf, 2009.
Köchy, M., and A. Freibauer: Workshop on mapping of soil carbon stocks at the global scale. COCOS Report D1.4.3. Johann Heinrich von Thünen Institut, Braunschweig, Germany, available at http://literatur.ti.bund.de/digbib_extern/dn049595.pdf, 2011 (last accessed 13 July 2011).

Lehner, B., and Döll, P.: Development and validation of a global database of lakes, reservoirs and wetlands, J. Hydrol., 296, 1-22, doi:10.1016/j.jhydrol.2004.03.028, 2004.

Loveland, T. R., Reed, B. C., Brown, J. F., Ohlen, D. O., Zhu, J., Yang, L., and Merchant, J. W.: Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data, International Journal of Remote Sensing, 21, 1303-1330, doi:10.1080/014311600210191, 2000.

Mäkilä, M.: Calculation of the energy content of mires on the basis of peat properties [In Finnish with English summary], Report of Investigation, 121, Geological Survey of Finland, Geological Survey of Finland, 1994.

McBratney, A. B., Mendonça, S., M.L, and Minasny, B.: On digital soil mapping, Geoderma, 117, 3-52, doi:10.1016/S0016-7061(03)00223-4, 2003/11//a.

McBratney, A. B., Mendonça Santos, M. L., and Minasny, B.: On digital soil mapping, Geoderma, 117, 3-52, doi:10.1016/S0016-7061(03)00223-4, 2003b.

Mitra, S., Wassmann, R., and Vlek, P.: An appraisal of global wetland area and its organic carbon stock, Current Science, 88, 25-35, 2005.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang: Anthropogenic and Natural Radiative Forcing, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (Eds), Cambridge University Press, Cambridge, UK, and New York, NY, U.S.A., 659–740, doi: 10.1017/ CBO9781107415324.018, 2013.

Nachtergaele, F. O.: From the Soil Map of the World to the Digital Global Soil and Terrain Database: 1960–2002, in: Handbook of Soil Science, Sumner, M. E. (Ed.), CRC Press, Boca Raton, H5-17, 1999.

Niu, Z. G., Gong, P., Cheng, X., Guo, J. H., Wang, L., Huang, H. B., Shen, S. Q., Wu, Y. Z., Wang, X. F., Wang, X. W., Ying, Q., Liang, L., Zhang, L. N., Wang, L., Yao, Q., Yang, Z. Z., Guo, Z.

Q., and Dai, Y. J.: Geographical analysis of China's wetlands preliminarily derived from remotely sensed data, Science in China – Series D: Earth Sciences, 39, 188-203, 2009.

Page, S. E., Rieley, J. O., and Banks, C. J.: Global and regional importance of the tropical peatland carbon pool, Glob. Change Biol., 17, 798-818, doi:10.1111/j.1365-2486.2010.02279.x, 2011.

Powlson, D. S., Whitmore, A. P., and Goulding, K. W. T.: Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false, European Journal of Soil Science, 62, 42-55, doi:10.1111/j.1365-2389.2010.01342.x, 2011.

Pregitzer, K. S., and Euskirchen, E. S.: Carbon cycling and storage in world forests: biome patterns related to forest age, Glob. Change Biol., 10, 2052-2077, doi:10.1111/j.1365-2486.2004.00866.x, 2004.

R Development Core Team: *R*: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, 2011.

Raich, J. W., Potter, C. S., and Bhagawati, D.: Interannual variability in global soil respiration, 1980–94, Glob. Change Biol., 8, 800-812, doi:10.1046/j.1365-2486.2002.00511.x, 2002.

Reich, P.: Soil organic carbon map, USDA-NRCS, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054018, last access: 2015-02-19, 2000.

Scharlemann, J. P. W., Tanner, E., V. J., Hiederer, R., and Kapos, V.: Global soil carbon: understanding and managing the largest terrestrial carbon pool, Carbon Management, 5, 81-91, doi:10.4155/CMT.13.77, 2014.

Shangguan, W., Dai, Y., Duan, Q., Liu, B., and Yuan, H.: A global soil data set for earth system modeling, Journal of Advances in Modeling Earth Systems, 6, 249-263, doi:10.1002/2013MS000293, 2014.

Stockmann, U., Malone, B. P., McBratney, A. B., and Minasny, B.: Landscape-scale exploratory radiometric mapping using proximal soil sensing, Geoderma, 239–240, 115-129, doi:10.1016/j.geoderma.2014.10.005, 2015.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Glob. Biogeochem. Cycles, 23, GB2023, doi:10.1029/2008GB003327, 2009.

Tarnocai, C., I. M. Kettles, and B. Lacelle: Peatlands of Canada database, Open File, 4002, Geological Survey of Canada, doi:10.4095/213529, 2002.

Turunen, J.: Development of Finnish peatland area and carbon storage 1950–2000, Boreal Environment Research, 13, 319-334, 2008.

Wei, X., Shao, M., Gale, W., and Li, L.: Global pattern of soil carbon losses due to the conversion of forests to agricultural land, Scientific Reports, 4, 4062, 2014.

Wieder, W. R., Boehnert, J., and Bonan, G. B.: Evaluating soil biogeochemistry parameterizations in Earth system models with observations, Glob. Biogeochem. Cycles, 28, 211-222, doi:10.1002/2013GB004665, 2014.

Yan, Y., Luo, Y., Zhou, X., and Chen, J.: Sources of variation in simulated ecosystem carbon storage capacity from the 5th Climate Model Intercomparison Project (CMIP5), Tellus Series B – Chemical and Physical Meteorology, 66, 22568, doi:10.3402/tellusb.v66.22568, 2014.

Zimov, S. A., Davydov, S. P., Zimova, G. M., Davydova, A. I., Schuur, E. A. G., Dutta, K., and Chapin, F. S.: Permafrost carbon: Stock and decomposability of a globally significant carbon pool, Geophys. Res. Let., 33, L20502, doi:10.1029/2006GL027484, 2006.

Table 1. Definition of terms with respect to organic soil carbon.

Term	Abbreviation/Acronym	Definition
Concentration	C_{org}	organic carbon mass/soil dry mass, C_{org}
Areal density (of fine soil)		C_{org} × depth × (1 – fractional volume of rocks, coarse roots, and ice)
Stock	m_C	areal density of fine soil integrated over all layers to a specified depth
Mass		stock integrated over a specified area
	BD	bulk density
	CAMP	Circum-Arctic Map of Permafrost and Ground Ice Conditions
	DSMW	Digital Soil Map of the World
	GLCC	Global Land Cover Characteristics database
	GLWD	Global Lakes and Wetland Database
	GPD	Global Peatland Database
	HWSD	Harmonized World Soil Database
	IGBP	International Geosphere Biosphere Program
	NCSCDB	Northern Circumpolar Soil Carbon Data Base
	PTF	pedotransfer function
	SMW	Soil Map of the World
	SOC	soil organic carbon
	SOTER	Soil and Terrain Database
	SOTWIS	Harmonized continental SOTER-derived database
	WISE	World Inventory of Soil Emission Potentials

Table 2. Changes to the global SOC mass in the top 1 m after each adjustment to the HWSD v.1.1 database.

processing step	SOC mass (Pg)
no adjustment	2469.5
(1) filling of missing values for C_{org}	2470.6
(2) and filling of missing values for BD	2471.3
(3a) and adjusting BD values when C_{org}>3%	1230.2
(3b) or replacing BD values only for Histosols	1113.3
(4) = (3a) and (3b)	1060.9

Table 3. Soil organic carbon masses 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. 1 $Mm^2 = 10^6 km^2$

Continent converted to 30" raster	**Soil area (Mm^2)**	**SOC mass, 0–1 m (Pg)** HWSD v.1.1-modified
Asia, incl. Malay Archipelago	42.0	369
North America, incl. Greenland, Central America	21.3	223
Europe, incl. Iceland, Svalbard, Novaya Zemlya	9.4	110
Africa, incl. Madagascar	27.2	148
South America	17.7	163
Australia, New Zealand, Pacific Islands	8.0	46
non-overlapping pixels	0.2	2
total (90°N – 60°S)	125.8	1061

Table 4. Organic carbon mass (top 1 m) of soils with gelic properties in HWSD v.1.1-adjusted. (All areas north of 60°S). Percentiles refer to the distribution of C stocks in each cell within the soil area mentioned. 1 $Mm^2 = 10^6$ km^2. Hist/soil: fraction of soil area covered by Histosols.

Gelic phase	**Cell area (Mm^2)**	**Soil area (Mm^2)**	**Hist/ soil**	**C stock (kg m^{-2}), percentiles**					**C mass (Pg)**
				5%	**25%**	**50%**	**75%**	**95%**	
continuous, >90% of area	5.46	5.30	12%	5.9	7.4	7.6	12.6	38	65.2
discontinuous, 50–90%	4.11	4.07	12%	6.4	6.5	9.5	15.8	28.9	51.8
sporadic, 10–50%	3.79	3.68	6%	3.8	8.3	12.5	15.6	19	45.3
isolated, 0–10%	0.05	0.05	86%	8.4	27.9	32.8	32.8	32.8	1.5
whole area	13.41	13.10	11%	5.3	6.9	9.8	15.6	30.6	163.8

Table 5. Comparison of organic carbon stocks (top 1 m) between HWSD v.1.1-adjusted and NCSCDB (Tarnocai *et al.* 2009). Permafrost contingency refers to the Circumarctic Permafrost Map. NCSDB used different soil areas within grid cells than HWSD. Percentiles refer to the distribution of C stocks in each grid cell within the soil area mentioned. 1 Mm^2 = 10^6 km^2.

	HWSD								**NCSDB**		
Permafrost contingency	Cell area (Mm^2)	Soil area (Mm^2)	C stock (kg m^{-2}), percentiles					C mass (Pg)	Soil area (Mm^2)	C stock (kg m^{-2}), mean	C mass (Pg)
			5%	25%	50%	75%	95%				
continuous, >90% of area	10.64	9.97	4.1	6.5	8	14.6	18.8	105.8	10.1	29.5	299
discontinuous, 50–90%	3.17	3.05	4.4	6.9	12.9	16.9	32.6	41.3	3.1	21.8	67
sporadic, 10–50%	3.08	2.94	4.9	7.4	12.7	17	35.5	40.3	2.6	24.3	63
isolated, 0–10%	3.67	3.55	5.6	7.8	10.1	16	32.3	45.4	3.0	22.6	67
whole area	20.55	19.52	4.4	6.9	9.4	15.5	28	232.7	18.8	26.4	496

Table 6. Area and spatial overlap of wetland types in GLWD and GLCC (grid cell area, Mm^2) within the extent of the HWSD.

GLWD		GLCC, ecosystems legend						
	area (Mm^2)	14 Inland Water 2.339	45 Marsh Wetland 0.062	13 Wooded Wet Swamps 0.083	72 Man-grove 0.048	44 Mire, Bog, Fen 0.797	36 Rice Paddy and Field 2.406	Dry-land 128.033
1–3 Lake, Reservoir, River	2.370	1.437	0.000	0.002	0.006	0.027	0.008	0.845
4 Freshwater Marsh, Floodplain	2.487	0.077	0.015	0.003	0.006	0.058	0.167	2.155
5 Swamp Forest, Flooded Forest	1.154	0.041	–	0.013	0.001	–	0.006	1.090
6 Coastal Wetland	0.413	0.015	0.001	0.007	0.011	0.002	0.026	0.321
7 Pan, Brackish/ Saline Wetland	0.433	0.002	<0.001	<0.001	<0.001	–	0.001	0.429
8 Bog, Fen, Mire	0.710	–	–	–	–	0.710	–	–
9 Intermittent Wetland/Lake	0.689	0.004	<0.001	<0.001	<0.001	–	0.003	0.681
10 50-100% Wetland	1.762	0.045	–	0.005	–	–	–	1.693
11 25-50% Wetland	3.153	0.065	–	<0.001	–	–	–	3.077
12 Wetland Complex (0-25% Wetland)	0.898	<0.001	–	–	–	–	0.046	0.846
Dryland	120.433	0.646	0.045	0.052	0.024	–	2.149	116.896

Table 7. Organic carbon stocks and masses in the top 1 m of *global* wetland soils derived from the HWSD v1.1-adjusted. Wetland extent is primarily defined according to the Global Lake and Wetlands Database (1–12), augmented by wetland in the GLCC (13–72). Percentiles refer to the distribution of C stocks in each grid cell within the soil area mentioned. SOC mass of permanent wetlands (types B–I) is 81.8 Pg, that of all wetlands except open waters (types B–K) is 158.1 Pg. 1 $Mm^2 = 10^6 km^2$. Hist/soil: fraction of soil area covered by Histosols.

Wetland type		Cell area	Soil area	Hist./soil	C stock (kg m^{-2}), percentiles					C mass (Pg)
	GLWD and GLCC category	(Mm^2)	(Mm^2)	%	5%	25%	50%	75%	95%	
A	1–3 Lake, Reservoir, River 14 Inland Water	3.01	2.11	7	4.2	6.5	9	14.2	24.6	22.8
B	4 Freshwater Marsh, Floodplain 45 Marsh Wetland	2.53	2.48	17	4.4	7	10	19.1	38	32.3
C	5 Swamp Forest, Flooded Forest 13 Wooded Wet Swamps	1.21	1.21	6	3.6	5.6	8.6	13.6	33.8	13.2
D	8/44 Bog, Fen, Mire	0.71	0.68	14	4.4	8.4	14.9	18.3	35.4	10.3
E	7 Pan, Brackish/ Saline Wetland	0.43	0.31	<1	2.8	4	4.7	5.4	7.5	1.5
F	6 Coastal Wetland 72 Mangrove	0.44	0.43	4	3.9	6.1	7.3	11.8	21.9	4.4
G	36 Rice Paddy and Field	2.15	2.14	<1	4.7	6	7.1	8.9	12.1	17.1
H	9 Intermittent Wetland/Lake	0.69	0.60	<1	2.3	3.6	4.4	5.9	9.6	3
I	10 50-100% Wetland	1.75	1.74	33	6.9	12.5	13.7	24.4	38	31.1
J	11 25-50% Wetland	3.14	3.11	10	5.6	8.8	12.3	14.6	28	38.5
K	12 Wetland Complex (0-25% Wetland)	0.9	0.89	1	5.8	5.9	5.9	7.3	12.6	6.7
Dryland		117.24	110.15	2	2.5	4.9	7.1	10.3	18.1	880

Table 8. Organic carbon stocks and masses in the top 1 m of *tropical* wetland soils derived from HWSD v.1.1-adjusted. Wetlands are classified primarily according to the Global Lake and Wetlands Database (1–12), augmented by wetland classes in the GLCC (13–72). Percentiles refer to the distribution of C stocks in each grid cell within the soil area mentioned. C mass of permanent wetlands (types B–H) is 38.3 Pg, that of all wetlands except open waters (types B–K) is 39.9 Pg. 1 $Mm^2 = 10^6 km^2$. Hist/soil: fraction of soil area covered by Histosols.

Wetland type		Cell area	Soil area	Hist./ soil	C stock ($kg\ m^{-2}$), percentiles					C mass (Pg)
	GLWD and GLCC category	(Mm^2)	(Mm^2)	%	5%	25%	50%	75%	95%	
A	1–3 Lake, Reservoir, River 14 Inland Water	0.76	0.49	2%	3.9	5.9	7.9	10.6	18.8	4.5
B	4 Freshwater Marsh, Floodplain 45 Marsh Wetland	1.27	1.26	6%	3.7	6.2	7.7	10.3	24.2	12.0
C	5 Swamp Forest, Flooded Forest 13 Wooded Wet Swamps	1.21	1.20	6%	3.6	5.6	8.6	13.6	33.8	13.2
D	8/44 Bog, Fen, Mire	0.0	0.00	0%	2.5	6.0	6.0	11.9	12.0	0.0
E	7 Pan, Brackish/ Saline Wetland	0.12	0.10	0%	2.5	3.2	4.3	5.3	7.5	0.5
F	6 Coastal Wetland 72 Mangrove	0.31	0.31	4%	4.0	6.1	8.5	13.7	25.7	3.4
G	36 Rice Paddy and Field	1.06	1.06	1%	5.1	6.2	6.9	8.1	13.2	8.4
H	9 Intermittent Wetland/Lake	0.22	0.20	0%	2.2	3.3	4.1	5.0	6.4	0.8
K	12 Wetland Complex (0-25% Wetland)	0.2	0.20	3%	5.0	5.9	6.5	8.2	13.2	1.6
Dryland		44.71	43.06	1%	2.2	4.3	6.1	8.5	15.2	310.6
Tropical area		49.87	47.88	1%						354.9

Figure captions

Figure 1. Global stock (a) and mass (b, per 5° latitude) of organic carbon in the top 1 m of the terrestrial soil calculated from HWSD v.1.1-adjusted.

Figure 2. Extent of permafrost in HWSD v.1.1. Colour scale: fraction of soil units within a 0.5' grid cell with 'gelic phase' (averaged for display to 30' resolution); red outline: permafrost attribute in HWSD supplementary data sets SQ1–7 at 5' resolution.

Figure 3. (a) Global distribution of important wetlands (by carbon mass) according to the Global Lakes and Wetlands Database and Global Land Cover Characterization. The most frequent wetland type is displayed within a 0.5° grid cell. Wetland types A-K are explained in Table 6. (b) Carbon mass in wetland soils (top 1 m) in bands of 5° latitude (calculated from HWSD v.1.1-modified). (c) Carbon mass in aggregated types of wetland soils (panel b).

Figure 4. Fraction of Histosol area per 0.5° grid cell according to HWSD v.1.1.

Figures

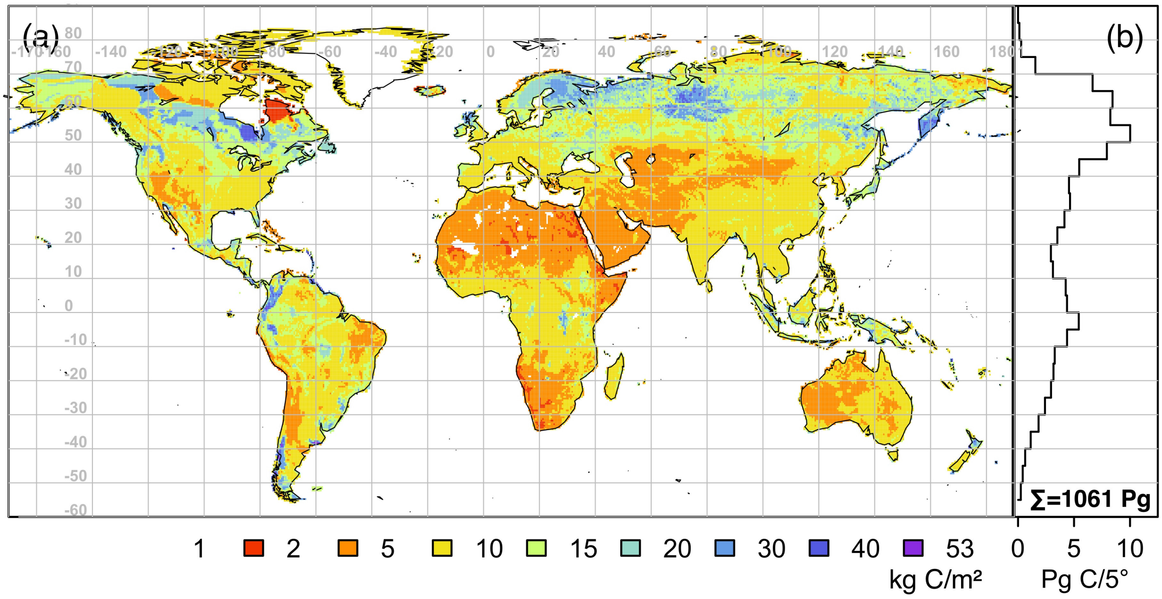

Figure 1. Global stock (a) and mass (b, per 5° latitude) of organic carbon in the top 1 m of the terrestrial soil calculated from HWSD v.1.1-adjusted.

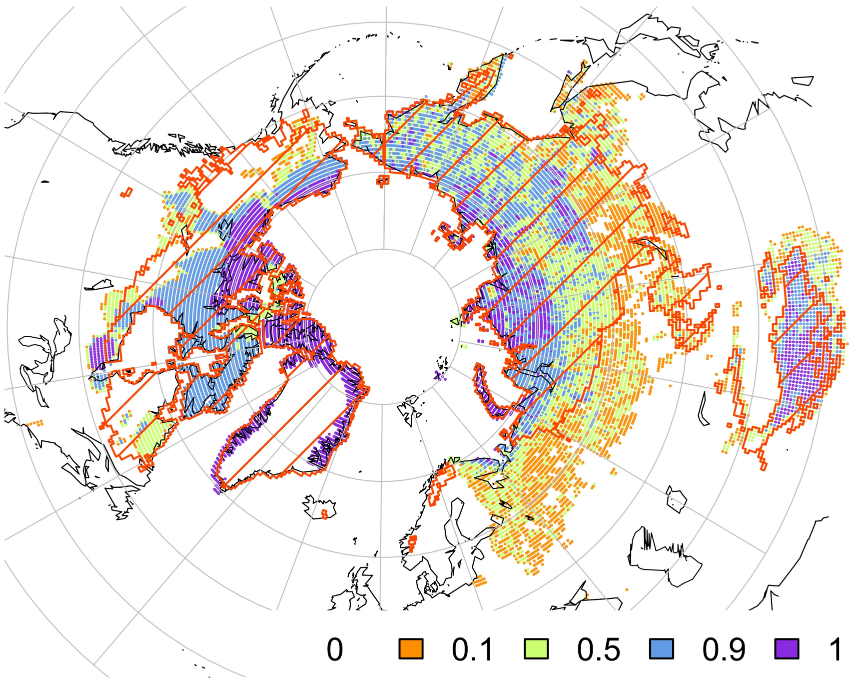

Figure 2. Extent of permafrost in HWSD v.1.1. Colour scale: fraction of soil units within a 0.5' grid cell with 'gelic phase' (averaged for display to 30' resolution); red outline: permafrost attribute in HWSD supplementary data sets SQ1–7 at 5' resolution.

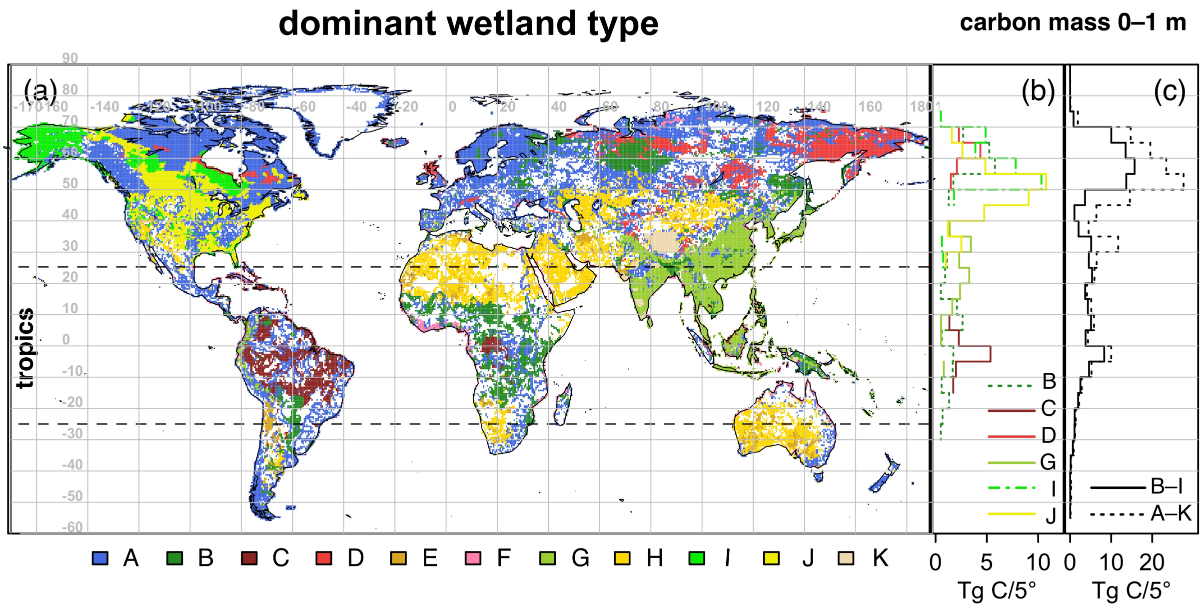

Figure 3. (a) Global distribution of important wetlands (by carbon mass) according to the Global Lakes and Wetlands Database and Global Land Cover Characterization. The most frequent wetland type is displayed within a 0.5° grid cell. Wetland types A-K are explained in Table 6. (b) Carbon mass in wetland soils (top 1 m) in bands of 5° latitude (calculated from HWSD v.1.1-adjusted). (c) Carbon mass in aggregated types of wetland soils (panel b).

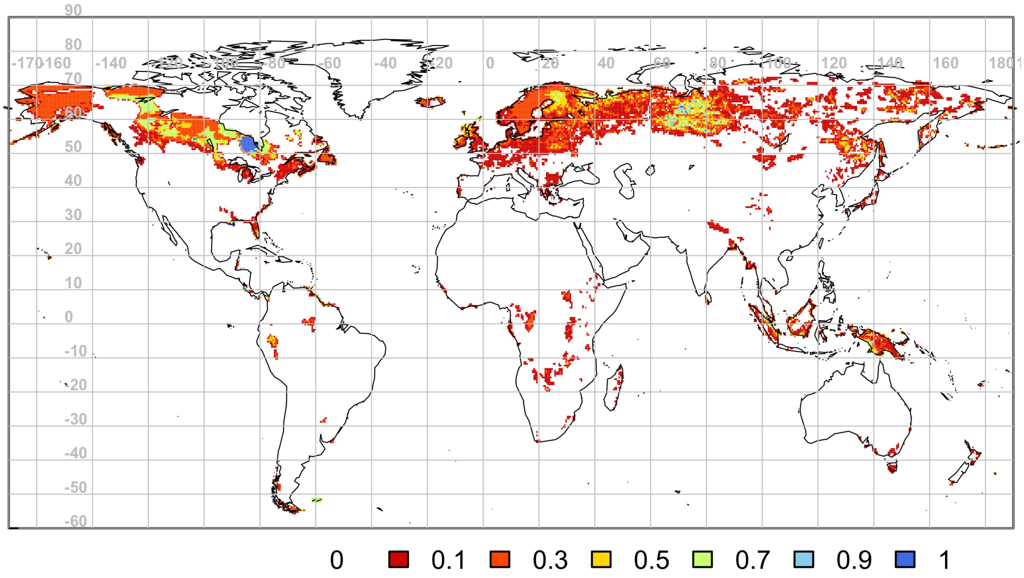

Figure 4. Fraction of Histosol area per 0.5° grid cell according to HWSD v.1.1.