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

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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) is greater than the combined mass of carbon (C) contained in the atmosphere and in the living biomass. Therefore, small changes in the mass of SOC can have profound effects on the concentration of atmospheric CO_2 and hence climate change. Despite its importance, the global mass of SOC and its distribution in space and among land-use/land-cover classes is not well known.

On the short to middle term (decades), variation in SOC mass is strongly related to the balance of input from net primary productivity 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, 1.2 – 1.8 g cm^{-3} is less consequential.

Traditionally, maps of the spatial distribution of SOC stocks are derived from maps where areas with similar soil characteristics are aggregated to form soil mapping units, and the SOC mass of the area of the soil mapping unit is calculated by multiplication of the area of the soil mapping 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 mapping 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 (PTF) 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 bulk density (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 stock ($m_C \times A$). Lateral variability, temporal variability, 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 mapping units are represented by soil profiles with complete characteristics. The latest ISRIC-WISE database (v.3.1) contains harmonized data of more than 10250 soil profiles (Batjes, 2009). 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, 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 compare previous estimates of the global SOC mass in the top 1 m of soil derived from spatial databases (maps) to the mass derived from the Harmonized World Soil Database (HWSD, FAO et al., 2012), which 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) but requires adjustment of bulk densities of organic soils (Hiederer & Köchy 2011). Based on the adjusted HWSD, our paper reports for the first time area-weighted frequency distributions of carbon stocks in the top 1m of soil, in particular for the large SOC stocks in wetlands, the tropics, and permafrost at high latitudes. Frequency distributions can be used to improve the assessment of accuracy in studies where SOC is an independent variable. We update the HWSD-derived global SOC mass using best estimates for the permafrost region, the tropics, and soil below 1 m depth from several additional sources. Our conclusions provide recommendations for improving global soil mapping.

2. Spatial databases of global soil organic carbon mass

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.

The Harmonized World Soil Database (HWSD vers. 1.2, FAO et al., 2012) with a raster of 0.5 arc minutes (0.5') 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 0.5' grid. 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)."

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%). At the same time, the true soil depth of Cryosols and Podsols can be expected to be deeper than the recorded depth in the databases, which, however, would be of no consequence for the estimated SOC mass of the top 1 m.

The global SOC mass calculated directly from the original HWSD (v.1.1) 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 Methods), we calculated a global mass of SOC in the top 1 m of soil of 1230 Pg in a first step and 1062 Pg in a second step.

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 (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.

3. Processing of HWSD data for spatial analyses

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 $\sum(m_{C,s} \times A_s/A)$.

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%, 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.

Despite the harmonization of the 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 (Supplement). 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. (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 filled missing values of BD for mineral soils in 27 cases. (3) 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 set BD to 0.1 kg/dm^3 for all Histosols in HWSD. With 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. Hiederer & Köchy (2011) used WISE-based corrections for BD (BD_{top} = –0.285 ln(C_{org} [%])+1.457 and BD_{sub} = –0.291 ln(C_{org} [%])+1.389 for C_{org} > 12%) that result in a higher a global C mass of 1376 Pg in step 3 but a very similar mass (1062 Pg) after the BD correction for histosols in step 4.

For comparison, total SOC mass derived from the unaltered 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.

The HWSD database was pre-processed and analyzed with R (R Development Core Team, 2011). Details of the calculations are presented in the Supplement. 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) and 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

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 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. 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). Supplementary data to the HWSD (Fischer et al., 2008) indicate 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 extent (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 extent (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. Tarnocai *et al*. (2009) used the CAMP's permafrost classification (excluding the Alps and Central Asian ranges, 20.5 Mm^2 grid cell area) 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 permafrost region (185 Pg). 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 contribution to the difference in mass than arising from definitions and extent is the greater SOC stock calculated from the NCSCDB (Table 4). In 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. 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.

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. In terms of IPCC A4 categories of confidence, 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. 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 Mm^2) which alone results in a range of 94–215 Pg SOC. 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.

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 International Geosphere Biosphere program. 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.

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. 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 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 available in the database for peatlands is very heterogeneous. For some countries only the total area of peatland is 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. The great variation demands that BD of peatlands actually 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.

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). In situ measurements of soil C_{org}, soil depth, and BD, however, must still be improved, collected, and made available for calculating global SOC mass.

4.4. *Carbon in the tropics*

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 carbon (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.

Only 6% of the area of each of the two C-richest tropical wetland types are categorized as Histosols in the HWSD, totaling 0.1 Mm^2. The total area of Histosol in the HWSD, 0.4 Mm^2, agrees 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. Consequently, their best estimate of SOC mass for tropical peatlands 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). 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.

For estimating total tropical SOC mass without depth limit, we add 3/4 of Page *et al*.'s best estimate for tropical peatland (66.5 Pg) to represent SOC deeper than 1 m to our estimate of SOC mass in the top 1 m, resulting in 421 Pg. (This addition, however, excludes SOC below 1 m outside peatlands.) Thus, peatlands 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.

5. Conclusions

5.1. Global carbon mass — reprise

Assuming that the assessment of Tarnocai *et al*. (2009) of the SOC mass in the permafrost region is more accurate than that of HWSD, we update the global SOC mass within the top 1 m to 1325 Pg (1062 [HWSD global SOC mass] – 233 [HWSD permafrost region SOC mass, Table 4] + 496 [Tarnocai *et al*.'s estimate] Pg). We can use the best estimates of the total SOC mass for the permafrost region (1672 Pg — including deep carbon and high carbon content deposits—, Tarnocai et al., 2009) and the tropics (421 Pg) and add it to the SOC mass outside these areas (473 Pg). This sum (2567 Pg) does not yet comprise SOC below 1 m outside the permafrost region and the tropics (389 Pg, Jobbágy and Jackson, 2000). Thus the total SOC in soil is estimated at about 3000 Pg, but large uncertainties remain, especially for depths >1 m.

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 SOC, Raich et al., 2002). The areal extent of peatlands, their depth, and BD 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 with respect to improved soil monitoring agree with more comprehensive recommendations by an international group of experts (Jandl et al., 2014). 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 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. 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 Northern Circumpolar Soil Carbon Base, 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.

5.2. 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.

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

Term	Definition
Concentration	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	areal density of fine soil integrated over all layers to a specified depth
Mass	stock integrated over a specified area

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

processing step	SOC mass (Pg)
no modification	2469.5
(1) filling of missing values for C_{org}	2470.6
(2) filling of missing values for BD	2471.3
(3) adjusting BD values when C_{org}>3%	1230.2
(–) replacing BD values only for Histosols	1113.3
(4) adjusting BD values for C_{org}>3% & replacing BD for Histosols	1060.9

Table 3. 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. 1 $Mm^2 = 10^6\ km^2$

Continent converted to 30" raster	**Soil area (Mm^2)**	**Carbon stock, 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-modified. (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-modified and NCSCDB (Tarnocai *et al.* 2009). Permafrost contingency refers to the Circumarctic Permafrost Map. NCSDB used different soil areas 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 of NCSDB	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	area (Mm^2)	GLCC, ecosystems legend 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-modified. Wetland extent is primarily 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. C 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-modified. Wetlands 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

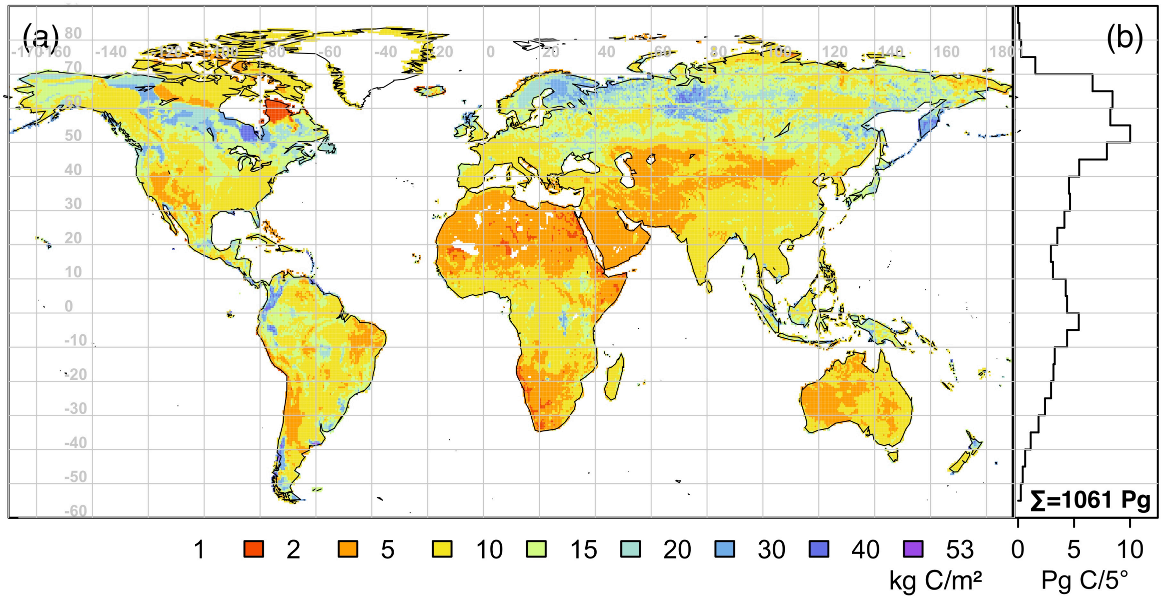
Figure 1. Global stock (a) and mass (b, per 5° latitude) of organic carbon in the top 1 m of the terrestrial soil calculated from HWSD v.1.1-modified.

Figure 2. Extent of permafrost in HWSD v.1.1. Colour scale: fraction of soil units within a 30" 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



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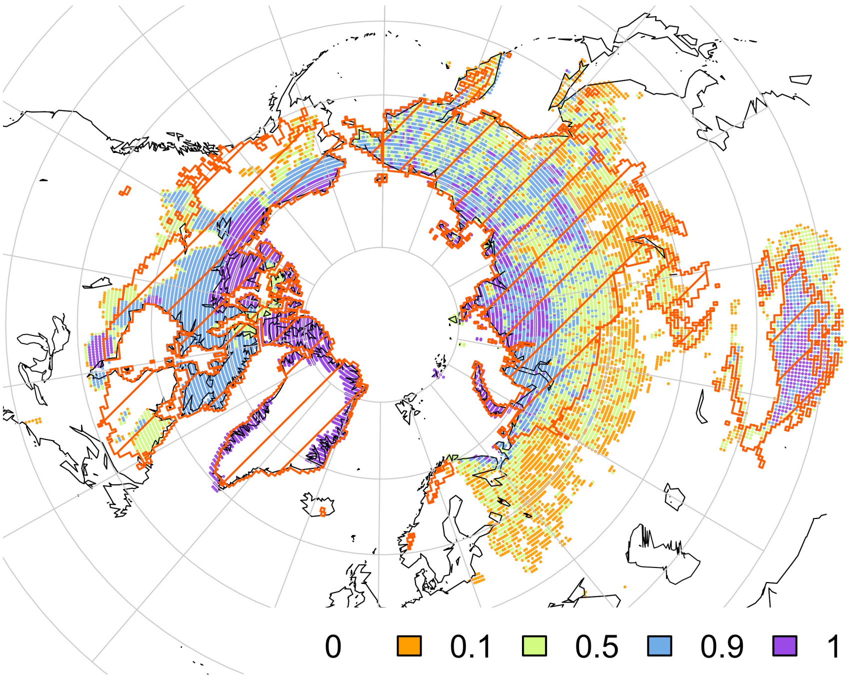

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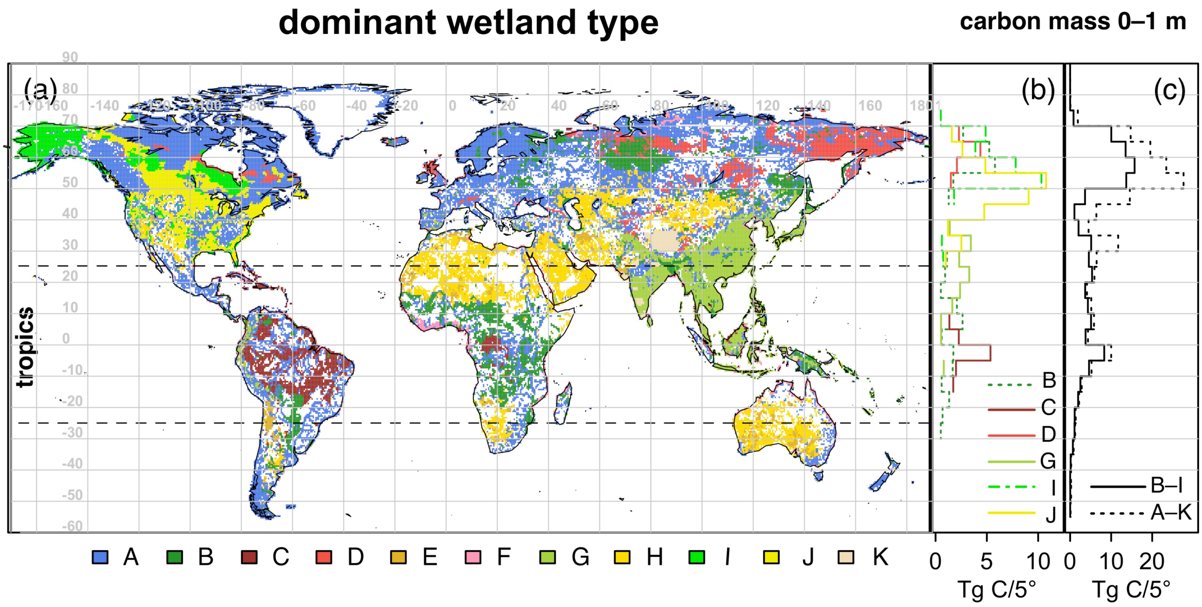

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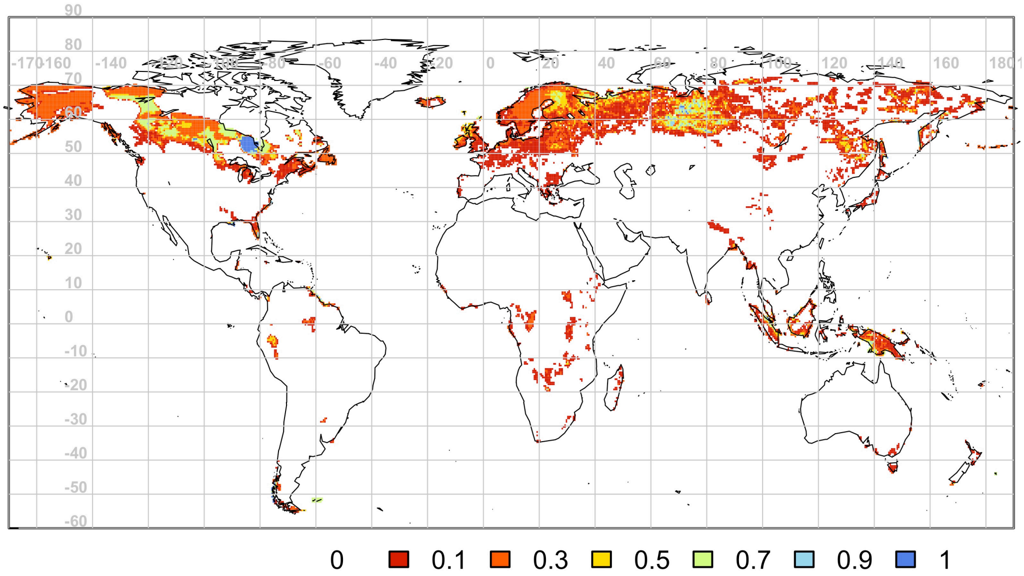

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