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Large differences in global and regional total soil carbon stock estimates based on SoilGrids, HWSD and NCSCD: Intercomparison and evaluation based on field data from USA, England, Wales and France

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Key points:

1. Estimates of the total soil organic carbon stock for global land mask are still quite diverse. Uncertainties associated with soil bulk density are higher and apply to all regions of the globe, whereas those of the carbon concentration are mostly marked at high latitudes.
2. Whatever the region considered, the SoilGrids, HWSD and NCSCD derived carbon stocks are not in agreement with the field data: Using field data gathered over USA, databases underestimate the stocks by 40% for SoilGrids and by 80-90% for HWSD. Using regional inventories over France and England and Wales, SoilGrids overestimates the carbon stock by 30% in the first case and by more than 150% in the second one.
3. It is possible that previous estimates of the total organic carbon stock have seriously underestimated organic carbon stock in northern latitudes, peatlands and wetlands.

Abstract

Soils are the major component of the terrestrial ecosystem and the largest organic carbon reservoir on Earth. However, they are a non-renewable natural resource and especially reactive to human disturbance and climate change. Despite its importance, soil carbon dynamics is an important source of uncertainty for future climate predictions and there is a growing need for more precise information to better understand the mechanisms controlling soil carbon dynamics and better constrain Earth system models.

The aim of our work is to compare soil organic carbon stocks given by different global and regional databases that already exist. We calculated global and regional soil carbon stocks at 1m depth given by three existing databases (SoilGrids, the Harmonized World Soil Database, and the Northern Circumpolar Soil Carbon Database). We observed that total stocks predicted by each product differ greatly: it's estimated to be around 3400 Pg by SoilGrids and is about 2500 Pg according to HWSD. This difference is marked in particular for boreal regions where differences can be related to high disparities in soil organic carbon concentration. Differences in other regions are more limited and may be related to differences in bulk density estimates. Finally, evaluation of the three datasets vs ground truth data shows that i) there is a significant difference in spatial patterns between ground truth data and compared datasets and that ii) datasets underestimate by more than 40% the soil organic carbon stock compared to field data.

Index terms and keywords

0428, 0434, 0486

Soil, Organic carbon, uncertainties, bulk density, datasets

1 Introduction

Climate change is "unprecedented with respect to scale, severity and complexity" [*Bäckstrand and Lövbrand,* 2015]. There has been a drastic increase in the atmospheric concentration of carbon dioxide (and of other greenhouse gases) since the industrial revolution. This increase in atmospheric CO_2 concentration is estimated to be about 31% since 1750 [*Lal*, 2004b], from the combustion of fossil fuel (405±20 Pg, [*Quéré et al.*, 2015]) and land use changes (190±65 Pg, [*Quéré et al.*, 2015]). Thus there is an urgent need to understand the major role of carbon with respect to climate change and therefore the short and long-term behavior of its various compartments. Within this framework, the global carbon cycle is typically composed by three large reservoirs interconnected through interchange pathways: the atmosphere, the terrestrial biosphere and the ocean. The carbon exchanges among reservoirs are the result of different chemical, physical and biological processes. Some stocks and flows among these reservoirs are relatively well quantified. For instance, about 120 Pg C yr^{-1} of atmospheric CO_2 is fixed by terrestrial biomass via photosynthesis [*Janzen*, 2004]. In parallel, the flux of CO_2 to the atmosphere from land use change was about 1.6 (0.5 to 2.7) Pg C yr^{-1} for the 1990s [*Denman et al.,* 2007]. However, there is still much debate about the carbon stored in terrestrial ecosystems [*Van der Werf G.D et al.*, 2009; *Harris et al.*, 2012; *Sanderman et al.*, 2017] and in particular in soils [*Köchy et al.*, 2015]. While the ocean constitutes the largest active carbon pool (including organic and inorganic carbon), soils are a major component of the terrestrial ecosystem and the largest organic carbon reservoir on Earth. However, large knowledge gaps

with regard to the functioning of this reservoir induce uncertainties in predicting its reaction to global change [*Schmidt et al.*, 2011; *Luo et al.*, 2016].

The global mass of soil organic carbon is greater than the combined mass of carbon contained in the atmosphere and in living biomass [*Ciais et al.*, 2013]. Soils contain 3.3 times the size of the atmospheric carbon pool and 4.5 times the size of the biotic carbon pool [*Lal*, 2004a]. In addition, soil is a non-renewable natural resource and is quite reactive to human disturbance and climate change. Even minor changes in global soil organic carbon (SOC) mass may have pronounced effects on atmospheric CO_2 concentrations and thus on climate change [*Jones et al.*, 2005; *Schuur et al.*, 2008]. Therefore, a better understanding of soil organic carbon stock and flows is essential for better carbon management and climate change mitigation policies, and also to help parameterize global circulation models used to guide climate policy. Unfortunately, despite its importance, the global mass of SOC and its distribution in space are not well known [*Jandl et al.*, 2014; *Scharlemann et al.*, 2014]. Although many estimates of global [*Amundson*, 2001; *Stockmann et al.*, 2015] and regional [*De Wit et al.*, 2006; *Tarnocai et al.*, 2009] SOC stocks have been published and the overall average value is generally estimated to be around 1500 Pg [*Batjes*, 1996; *Köchy et al.*, 2015], this value tends to vary considerably. A meta-analysis using 27 studies estimating global SOC mass by Scharlemann et al. [2014] asserted that the median value of the estimated SOC mass is about 1460.5 Pg and varies from 504 to 3000 Pg. This implies that, despite the large quantity of carbon stored as soil organic carbon and despite a great deal of research, there remains substantial uncertainty on the size of global SOC stocks and their spatial distribution [*Scharlemann et al.*, 2014]. This may be explained by the numerous factors controlling SOC dynamics and all the associated uncertainties as well as all the difficulties inherent in measuring and estimating carbon concentrations and bulk density [*Köchy et al.*, 2015].

Besides meta-analyses of field data, several global land information systems already exist. They are of paramount importance for land systems models that fail to properly represent carbon stocks in soils [*Todd-Brown et al.*, 2014] thereby inducing strong uncertainties for future stock estimation [*Nishina et al.*, 2014] and climate predictions [*Arora et al.*, 2013; *Arora and Boer*, 2014]. To our knowledge, however, these have never been compared. These products exhibit both similarities and differences in the methods and collected field data. Indeed, while based on the same regional data sources, they use different methods of stock estimation (pedotransfer functions), so uncertainties on global soil carbon stock may arise not only from sampling of soil-profile data but also from differing approaches to stock calculations and estimations.

Objectives of our work are in line with the growing need for global and specific information on the carbon stock in soils so more accurate predictions can be made. Our aim is therefore to compare the total numbers of organic carbon stock as well as the spatial distribution of organic carbon and to assess important factors contributing to differences in estimations of soil carbon stocks.

2 Materials and methods

Two types of data were used:

- Databases estimating soil properties that draw on field data, yet use different gap filling and calculation/mapping approaches in order to estimate soil properties on a more generalized scale. These include SoilGrids [*Hengl et al.*, 2017] and the Harmonized World Soil Database

(HWSD) [*Batjes*, 2016] for global maps, as well as the Northern Circumpolar Soil Carbon Database (NCSCD) [*Hugelius et al.*, 2013a, 2013b] for high latitude regions.

- Field data which consist of point measurements of carbon stocks on selected profiles available within the International Soil Carbon Network (ISCN) [*ISCN*, 2012], the National Survey Inventory of England and Wales (NSI) [*Bellamy et al.*, 2005] and the Réseau de Mesures de la Qualité des Sols of France (RMQS) [*Arrouays et al.,* 2003; *Jolivet et al*., 2006] .

In all cases, stocks are measured from the top of the mineral soil. For the datasets, the depth of 1 m was chosen in order to compare the products with each other (Table 1). Thereafter, to compare the databases with the measurements, the stocks are compared on the same minimum available depth. For instance, in the case of France, since the stock is supplied at a depth of 50 cm, the comparison with the SoilGrids database was made taking into account the stock at 50 cm depth only.

2.1 Datasets estimating carbon stocks in soil

2.1.1 SoilGrids

SoilGrids is a global soil information system containing spatial predictions for several soil properties (clay, silt and sand content, pH index, cation-exchange capacity …), at seven standard depths: 0 cm, 5 cm, 15 cm, 30 cm, 60 cm, 100 cm and 200 cm [*Hengl et al.*, 2014, 2017]. Altogether approximately 110,000 world soil profiles are used to generate this dataset. The dataset (April 2017 version) can be downloaded here: ftp://ftp.soilgrids.org/data/. A selection of the SoilGrids data is available as zipped datasets with a growing selection from 250 m to 10 km resolution. In this study, we used the 5 km resolution files (layers from 0 to 1m depth) which we aggregated to 0.5 degree resolution using a linear interpolation (SoilGrids in tables and figures).

For SoilGrids, we first calculate the carbon content (OCC (wt %)), the bulk density (BD (kg m^{-3})) and the gravel content (G (vol %)) for each standard layer (0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm) as below, according to Hengl et al. [2017]:

$$OCC_{a-b} = \frac{1}{2}\,\frac{1}{b-a}\sum\,(b-a)(OCC_a + OCC_b) \qquad (1)$$

$$BD_{a-b} = \frac{1}{2}\,\frac{1}{b-a}\sum\,(b-a)(BD_a + BD_b) \qquad (2)$$

$$G_{a-b} = \frac{1}{2}\,\frac{1}{b-a}\sum\,(b-a)(G_a + G_b) \qquad (3)$$

Where a and b are the lower and upper limits respectively of the standard depths.

Then, the soil organic carbon stock (SOC, (kg m^{-2})) was calculated, for each layer, using the following equation:

$$(SOC)_{a-b} = (OCC)_{a-b} * (BD)_{a-b} * (1 - G_{a-b}) * D_{a-b} \quad (4)$$

Where D is the layer thickness (m).

Finally, the total SOC was then summed on the full soil depth (1 m).

2.1.2 Harmonized World Soil Database (HWSD)

HWSD contains a collection of geographic information on soil physical and chemical properties from regional and national inventories all over the world [*Batjes*, 2016]. The HWSD is organized in mapping units, each consisting of particular combinations of different soils [*FAO,* 2012].

HWSD database provides soil properties for the topsoil (0 cm to 30 cm) and the subsoil (from 30 cm to 100 cm depth) layers only.

Soil organic carbon stock (SOC, (kg m^{-2})) was calculated, for each layer, using the following equation:

$$(SOC)_{0-30\,cm} = (OCC)_{0-30\,cm} * (BD)_{0-30\,cm} * (1 - G_{0-30\,cm}) * D_{0-30\,cm} \quad (5)$$

$$(SOC)_{30-100\,cm} = (OCC)_{30-100\,cm} * (BD)_{30-100\,cm} * (1 - G_{30-100\,cm}) * D_{30-100\,cm} \quad (6)$$

Where OCC (wt %) is the organic carbon content, BD (kg m^{-3}) is the bulk density, G (vol %) is the gravel content or the coarse fragments and/or segregated ice content and D is the layer thickness (m). The total SOC was then summed on the full soil depth (1 m).

One particularity of this database is that there are two different ways to estimate soil bulk density from soil properties: i) the SOTWIS bulk density values estimated by soil type and depth (HWSD_SOTWIS in tables and figures) and ii) the Saxton bulk densities, calculated from equations developed by Saxton et al. [1986] (HWSD_SAXTON in tables and figures). This equation relates the bulk density to the texture of the soil only.

Thanks to these different methods of bulk density calculations, we were able to calculate two carbon stock values from the same dataset. The data is available in the form of a 30 arc-second raster database and can be downloaded at http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/. As mentioned in table 1, we aggregated the data to 0.5 degree resolution for this study too using a linear interpolation.

2.1.3 Northern Circumpolar Soil Carbon Database (NCSCD)

NCSCD is a spatial dataset which quantifies storage of organic carbon in soils of the northern circumpolar permafrost region [*Hugelius et al.*, 2013a, 2013b], from 45°N to 90°N. The spatial data covers permafrost-affected areas in Alaska, Canada, the contiguous US, Europe, Greenland, Iceland, Kazakhstan, Mongolia, Russia and Svalbard.

The NCSCD contains many thousands of polygons (>78 000) and information on soil organic carbon (kg m^{-2}) between 0 cm and 300 cm depth and at different spatial resolutions. For this database, only the total carbon stock values are directly available in kg C m^{-2}.

The dataset can be downloaded at http://bolin.su.se/data/ncscd/. The data is stored as multiple netCDF-files and at different spatial resolutions: 1°, 0.5°, 0.25°, 0.1°, 0.05° and 0.012°. In this study we used the 0.5° resolution data.

2.2 Field data for soil Carbon stocks

2.2.1 International Soil Carbon Network (ISCN)

The ISCN database [*ISCN*, 2012] currently includes data for over 257,000 individual soil layers collected from over 41,000 profiles all around the world but mainly located in North

America. The 1m soil stock provided (30,691 points over the world and mainly in North of America) is the sum of its component layers, which may have been sampled by horizon or depth [*Cleve et al.*, 1993; *Michaelson et al.*, 1996; *Bockheim et al.*, 1998, 1999, 2001, 2003, 2004; *Jorgenson*, 2000; *Johnson et al.*, 2003; *Kristen et al.*, 2004; *Kane et al.*, 2005; *Neff et al.*, 2005; *Ping et al.*, 2005; *Harden et al.*, 2006; *Myers-Smith et al.*, 2007; *Schuur et al.*, 2007; *Jorgenson et al.*, 2008, 2009; *Vogel et al.*, 2008; *Kane and Vogel*, 2009; *Boby et al.*, 2010; *Ping and Michaelson*, 2010; *O'Donnell et al.*, 2011; *Yarie and LTER*, 2014]. The dataset can be downloaded at http://iscn.fluxdata.org/.

2.2.2 Network of Soil Quality Measurements (RMQS)

The RMQS [*Arrouays et al.,* 2003; *Jolivet et al*., 2006] database is based on 2,200 monitoring sites distributed uniformly over the French territory, according to a mesh 16-km x 16-km squares. It provides total carbon stock at the upper 50 cm of soil. Multiple added information is available on each site, e.g. vegetation description, environment description, profile sample collection history and laboratory analyses.

2.2.3 National Soil Inventory of England and Wales (NSI)

The NSI database covers England and Wales on a 5 km grid. 5,662 sites were sampled for soil [*Bellamy et al.*, 2005] and the total soil organic carbon was provided on 95 cm depth. NSI provides a very detailed soil description including stone abundance, root descriptions and boundary information.

2.3 Soil Properties, Net Primary Productivity (NPP) and climate data

In order to highlight the potential reasons for differences in the results given by the databases and also to determine relationships between soil properties and carbon stocks, different data provided by the databases (SoilGrids and HWSD) were used: organic carbon concentration (OC), bulk density (BD), clay, sand and silt content (soil texture), soil pH and cation-exchange capacity (CEC). After the soil properties, external properties such as climate data (precipitation and temperature) from the Global Precipitation Climatology Center (GPCC) and the total NPP provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) product were also used for the same purpose mentioned above. The MODIS-NPP data product was obtained through the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/data_access) and the 0.5° global climate forcing product (1901-2007) was developed for the third phase of GSWP3 (http://hydro.iis.u-tokyo.ac.jp/GSWP3/), based on the 20th Century Reanalysis (20CR) version 2 performed with the National Centers for Environmental Prediction (NCEP) land-atmosphere model [*Compo et al.*, 2011].

Table 1 summarizes the main features of the different databases. Table 2 gathers the total carbon stock calculated from the three databases/products. To enable comparison between the different databases, we decided to make the calculations on the same upper (0 - 1m) layer and at the same spatial resolution (0.5°; a classical resolution used for land surface models

running at global scale).

3 Results

3.1 Latitudinal distribution of the global soil carbon stock on 1 m depth

The distribution of carbon stocks along a latitudinal gradient (Figures 1, 2) for both global databases (SoilGrids and HWSD) presents a similar pattern with increasing values from the equator to the North Pole. This increase is more pronounced in the case of the SoilGrids database. Regarding the HWSD dataset (Figures 1b and 1c), the carbon stock values are higher when calculations were made with SAXTON bulk density, particularly at the high latitudes.

The major difference between the databases is observed at high latitudes (Figure 2); between 60°N and 90°N, the latitudinal profile shows a significant peak for SoilGrids and a slightly less marked peak for HWSD_SAXTON. Yet this peak is less important in the case of HWSD_SOTWIS and even lower with NCSCD. Between 50°N and 50°S, we note that the curve of SoilGrids and that of HWSD are closer. Finally, SoilGrids again shows an important peak, followed in this case by HWSD_SOTWIS.

3.2 The stocks estimated by each product on 1 m depth

Firstly, we note that the total carbon stock values (Table 2) greatly vary from one database to another and also within the same database (HWSD) according to the method of bulk density estimation (2439 and 2798 Pg C at global scale for SOWTIS and SAXTON, respectively). Furthermore, the value provided by SoilGrids (3421 Pg C) is at least 1.4 higher than those provided by HWSD.

Second, the regional distributions of carbon stocks over the three large latitudinal bands of the three databases (Table 2) are also not in agreement. The highest percentage (37 to 44%) of carbon is recorded in temperate regions, except for in HWSD_SOTWIS where the highest value is recorded in the tropics (44%). In boreal regions, the percentage is 34% for SoilGrids and 29% for HWSD_SAXTON. It is however lower (16%) when the SOTWIS bulk density is used. Finally, in the tropics, SoilGrids and HWSD_SAXTON have the lowest value (25%) and HWSD_SOTWIS has the highest (44%).

For the HWSD dataset, higher SOC stocks are recorded in the boreal zone when using SAXTON bulk density estimations, while higher values are recorded in the tropics with SOTWIS bulk density values. Overall, in the boreal and temperate regions, SoilGrids recorded the highest values (up to four times the values of NCSCD for the boreal zone). For the tropics, values provided by the two datasets are almost close to each other. For the boreal zone, we note that the carbon stock estimated in all three cases are higher than the NCSCD estimations.

3.3 The SOC distribution within depth (up to 1 m deep)

At the global and regional scale, the lowermost values of the HWSD carbon content profiles are lower than those of SoilGrids (Figure 3). However, both databases yield a similar general trend: high carbon content in the first 30 centimetres that then decreases with depth. The dissimilarity between the products/databases is almost the same for surface soil and for deep

soil.

At the surface and in deep soil, we recorded the highest value of SOC stock in the boreal region, and the lowest one in the tropics (Figure 3b, 3c and 3d). In the boreal region, the difference between SoilGrids and HWSD and NCSCD is very pronounced. This difference is less significant between HWSD_SOTIWS and NCSCD. Overall, the lowest values are recorded with NCSCD.

3.4 Identifying sources of discrepancies

SOC stocks are the result of eq. 1, which multiplies carbon concentration by bulk density. Both represent a source of discrepancy between products. To estimate whether products differ as a result of carbon concentration, bulk density, or both, we compared each factor for products with available information (HWSD and SoilGrids) at 1 m depth.

The difference in organic carbon concentration (OC %) distribution for both global databases, illustrated in Figure 4 (OC_SoilGrids – OC_HWSD), confirms once again that the main difference is located at high latitudes. Indeed, above 50°N, SoilGrids provides carbon concentration values much higher than those of HWSD, with the absolute difference becoming greater than 5%. On the remaining part of the globe, however, this difference is not very pronounced. It varies only between -0.5 and 0.5%.

The heterogeneity of the database dissimilarity is even greater for the bulk density (Figure 5). The first two maps (Figure 5a, 5b) correspond to the gap between the bulk density of SoilGrids and that of HWSD_SOTWIS and HWSD_SAXTON, respectively. In the tropics, SoilGrids provides higher bulk densities than HWSD with differences ranging from 300 to more than 500 kg m^{-3}. At high latitudes, SoilGrids yields much lower bulk density values than SAXTON (values globally are less than -100 kg m^{-3}, even if opposite trends are sometimes observed) and higher values than SOTWIS bulk density.

Figure 5c presents the dissimilarity between the SAXTON and SOTWIS bulk densities. SAXTON generates higher bulk density at high latitudes (from 50 kg m^{-3} to more than 500 kg m^{-3}) and also in the tropics. In some temperate regions, higher values are instead recorded with SOTWIS. These values may even be quite negative (up to -100 kg m^{-3}).

3.5 Benchmark using field measurements

Figure 6 illustrates the comparison between the soil organic carbon stocks derived from the databases and the field data: for each point, the carbon stock estimated from the database was plotted against the corresponding observed stock. However, a correspondence to all measured points was not always possible, as some points are not found in the global and regional databases (missing data). This explains the varying number of points from one graph to another.

At the global scale (Figure 6a, 6b, 6c), all the products estimating SOC (SoilGrids, HWSD_SOTWIS and HWSD_SAXTON) provide lower stocks than expected from field measurements (compared to ISCN). Indeed, the slopes of the scatter plots vary from 0.1 to 0.6. However, SoilGrids is the closest to the measurements with a slope very close to 1 (0.6).

At the regional scale, SoilGrids overestimates the carbon stock compared to the measurements over France (Figure 6d) as well as over England and Wales (Figure 6e), with slopes of 1.3 and

2.7, respectively.

Variability in the value of the carbon stock given by the different databases is therefore quite pronounced. This can be explained in part by errors generated by the intra-pixel variability.

3.6 Driving factors for SOC stocks

Table 3 gathers the slopes obtained for HWSD and SoilGrids from the graphs of carbon stock according to the different properties of the soil (texture, pH and CEC) on 1 m depth. The table presents the results of possible correlation of carbon stock to different soil properties: clay content, silt content, sand content, pH or CEC. Overall, both databases show the same trends: negative slopes for clay, sand and pH and positive slopes for silt and CEC. R^2 is quite low in all cases, while the slopes are almost equal in absolute value. For example, the values for clay vary from -0.2 to -0.7, those for sand from -0.05 to -0.07 and for silt from 0.2 to 0.3.

The same thing was done according to the climate (Table 4). In all cases, the same trend according to temperature and precipitation was observed: negative slopes for SoilGrids and HWSD. However, slopes for precipitation are different from SOTWIS to SAXTON (The value for the first is divided by 2 compared to the second) and the R^2 are quite low. For the temperature, the slope values are within -0.02 to -0.05 (kg m^{-2} °C^{-1}) and the R^2 are very low as well. It is interesting to note that despite the large differences in the predicted stocks, the relationship between SOC stocks and air temperature are rather similar for all products.

Finally**,** the relationship using NPP predicted by MODIS and the SOC stock was investigated at regional scale (Table 5). The slopes for the boreal region are high and positive for SoilGrids (165) and for HWSD (103 with SOTWIS bulk density and 200 with SAXTON bulk density). It is also positive with both databases in temperate and tropical zones, with a mean slope of around 10.

4. Discussion

The carbon cycle is a fundamental part of life on Earth and its equilibrium is a function of three reservoirs: the ocean, the atmosphere and the terrestrial biosphere [*Ciais et al.*, 2013]. These three reservoirs interact and exchange carbon with each other. Nonetheless, soils represent the largest reservoir of terrestrial organic carbon. They interact strongly with atmospheric composition and climate. Furthermore, the role of soil carbon in climate dynamics is one of the largest uncertainties in earth system models used to predict future climate change [*Davidson and Janssens*, 2006].

SOC mass is a product of several factors (e.g. organic carbon concentration, bulk density and coarse fragments [*Poeplau et al.*, 2017]). Consequently, uncertainties and errors in measurement and estimation in just one of the factors may affect the final SOC stock calculation. Therefore, it is unsurprising to see wide variations in carbon stock estimates from one database to another, and even within the same database when using different measurement methods and different subdatasets. Understanding and quantifying sources of this variability is key to estimating the soil carbon stock at the global scale, since the probability of errors increases with increasing spatial scale [*Xu et al.*, 2016; *Zhang et al.*, 2016].

Firstly, we note that the values of SOC stock output by SoilGrids were always higher compared to the other estimations; even the total value of 1m SOC stock at the global scale

(3421 Pg) is high compared to previous studies [*Batjes*, 1996; *Köchy et al.*, 2015]. It is therefore very likely that previous estimates of the total organic carbon stock have seriously underestimated organic carbon stock in northern latitudes, peatlands and wetlands. This suggests that the value of the total carbon stock provided by SoilGrids may be the closest one to reality. In fact, when compared to field data (Figure 6), estimates of SoilGrids are very close to measurements with slopes of 0.6 (at the global scale) and 1.3 (at the scale of France).

Secondly, the lower values of SOC recorded with HWSD can be explained in part by a poor depiction of wetlands and permafrost soils, which represent a large fraction of the total soil carbon stock, especially at high northern latitudes [*Köchy et al.*, 2015].

Finally, SOC calculated from SAXTON bulk density in the HWSD database was higher than that calculated with SOTWIS bulk density. This is mainly because the bulk density is overestimated for soils with high porosity or with high organic matter content when using the SAXTON method [*Köchy et al.*, 2015; *Saxton et al.,* 1986].

Temperate regions account for the major part of the total carbon stock (between 37% and 44%). This is no doubt related to the very high amount of overall landmass located at temperate latitudes rather than to a higher capacity to store carbon; the temperate region accounts for 2.5 times the area of the tropics and 3.5 times the boreal land surface. Thus, relative to the surface, the boreal region stores a very high amount of carbon mainly because of the presence of permafrost and wetlands.

In the tropics, carbon stock values are lower compared to temperate and boreal regions. This reflects the known higher decomposition rate of carbon under high temperatures and frequent precipitation. More striking is that this region yields smaller differences between databases than other regions. This is due to the fact that most databases use the same original data sources (The Soil Map of China, SOTER, IS, etc.) which unfortunately do not reflect minimal uncertainties.

The different products are thus quite different at the global scale and in particular in the boreal zone. They are slightly less dissimilar in temperate zones and quite similar in the tropics.

Dissimilarities between database-derived stocks are also evidenced along the profile. Firstly, this variability in the surface can be explained by the influence of climate and vegetation cover on soil stocks [*Carvalhais et al.*, 2014], which is evidently more pronounced on the surface and which therefore contributes to greater variations than expected. Secondly, the carbon stock is intimately linked to environmental and climatic conditions, while carbon inputs are linked to primary production and finally to intrinsic factors such as soil type [*Doetterl et al.*, 2015].

Whatever scale is considered, the database-derived carbon stocks are not in agreement with the field data: when using data gathered from different locations all over the world, the databases underestimate the stocks, whereas at the scale of the field analyzed regions, they overestimate it. Figure 6 (panels a to c) clearly highlights the underestimation of the carbon stock by the datasets compared to field data, only with SoilGrids, this underestimation is much less pronounced and the estimated values are much closer to the field data (slope equal to 0.6).

At the regional scale (Figure 6d and 6e), the results are quite different. The national inventories (France, England and Wales) show that SoilGrids tend to overestimate the SOC stock. However, again, the slope is 1.3 in the case of France showing that the estimates are rather not very high compared to the measurements. Then, the elevated slope in the case of

England and Wales (2.7) does not really reflect an important overestimate because, in this case, very little correspondences was found. This overestimation can also be explained in part by errors generated by the intra-pixel variability.

Nevertheless, some common factors between the databases may be identified. For instance, SOC stock might be related to different soil properties (e.g. texture, pH, CEC) [*Barré et al.*, 2017], which obviously impact carbon decomposition rate in the soil. Looking at the results, overall the trends are similar and slopes in absolute values are very close between the databases.

Furthermore, SOC stocks are negatively correlated with temperature and precipitation. The relation between soil temperature, moisture and SOC stocks is controlled by two factors. First, the effect of plant primary production controlling the inputs and secondly the microbial activity and the associated heterotrophic respiration controlling the outputs. Primary production and microbial activity are both controlled by temperature and moisture [*Piao et al.*, 2006; *Moyano et al.*, 2012; *Sierra*, 2012] with non-linear interaction [*Manzoni et al.*, 2004]. Here the negative slopes observed suggest that climate effect on inputs are less than those on outputs since precipitation and temperature stimulate the decomposition of organic matter. Some tendencies (SOC according to climate, pH, etc.) are therefore similar between datasets but the slopes of the relationship are often not.

Current carbon sequestration studies strongly need good quality data for bulk density and carbon concentration. To calculate the carbon stock in the soil, the bulk density is multiplied by the organic carbon, and thus the uncertainties associated with the measurements are multiplied together. The diversity of soil layers in thickness, properties, texture and depth requires several methods of measurement which may not give the same values for carbon concentration and bulk density, and this is only on a single profile of the same soil [*Manrique and Jones*, 1991; *Heuscher et al.*, 2005; *Martin et al.*, 2009]. The difference of course only increases as we try to make estimates at the global scale. The solution will be just to try to minimize uncertainties to the maximum.

However, according to the comparisons, the differences between the databases regarding the carbon concentration (Figure 4) are less marked than those regarding the bulk density (Figure 5). This only suggests that the uncertainties associated with bulk density are higher and also apply to all regions of the globe (whereas those of the carbon concentration are most marked at high latitudes). This underlines the importance of bulk density; bulk density is considered in most soil studies and analyses and is a key soil property for the assessment of carbon stocks [*Lobsey and Viscarra Rossel*, 2016], and is one of the most important parameters for calculating SOC storage. For instance, Köchy et al. [2015] applied several corrections on bulk density measurements, in particular for organic soils using HWSD, and showed that these corrections could lead to a reduction of carbon stock by a half. These same corrections were applied to the SoilGrids data (not shown in this paper): the bulk density values were first adjusted for soils with a carbon concentration of more than 3%. For this, a new value of this bulk density was calculated using an equation based on an analysis of the SPADE/M2 soil profile database *[Hiedereret al., 2010]* (see [*Köchy et al.*, 2015] for more details). Subsequently, the value of 0.1 kg dm^{-3} was assigned to the bulk density for all Histosols.
For SoilGrids, the effect of these modifications was indeed less significant; the stock decreased by 1000 Pg (a decrease by 27% of the initial stock against 50% in the case of HWSD).

Furthermore, data on bulk density are often absent in various regions of the globe, for example in Central Africa [*Botula et al.*, 2015]. This is because such *in situ* measurements can be difficult and time-consuming, especially at large spatial scales [*Sequeira et al.*, 2014]. As a result, various methods for estimating bulk density are often used to fill missing bulk density data, such as mean, median and particularly pedo-transfer functions. It is from these different methods that high uncertainty in SOC storage estimates arise. Pedo-transfer functions are useful for coping with this lack of data, but the associated uncertainties require better quantification in order to understand the effect of using such functions on large-scale estimations of bulk density [*Xu et al.*, 2015].

5. Conclusion

Soils are the major component of the terrestrial ecosystem and the largest organic carbon reservoir on Earth. They also represent an important source of uncertainties for future climate predictions. We calculated global and regional soil carbon stocks with three global databases (SoilGrids, HWSD, and NCSCD) at different depths and we observed that they differ greatly, particularly in boreal regions. Differences in boreal regions may be due to high disparities in organic carbon concentration, whereas differences in other regions are more likely due to different bulk densities. Finally, we compared the three products with field data available within the International Soil Carbon Network and two regional datasets (RMQS and NSI). We observed that each product presents certain challenges in terms of representing the spatial variability. The estimation of the global soil carbon stock is still quite uncertain and improved geostatistical methods are urgently needed to reduce the confidence interval of the most important organic carbon stock.

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Figure 1. Global distribution of carbon stock on the [0;1 m] upper layer in the global scale (kg C m^{-2}) and for the different databases

Figure 2. The total carbon stock (kg C m^{-2}) on the [0;1 m] upper layer per latitude and for the different databases

Figure 3. The carbon profiles (Kg C m^{-3}) on the global and regional scales; the symbol is located at the lower depth of the corresponding layer

Figure 4. Global distribution of organic carbon concentration (kg/100 kg): Difference between SoilGrids and HWSD on the [0;1 m] upper layer

Figure 5. Global distribution of bulk density (kg m^{-3}): Difference between SoilGrids and HWSD on the [0;1 m] upper layer

Figure 6. Datasets comparison: For every location that corresponds to an analyzed soil profile recorded in the field databases, the corresponding carbon stock was estimated from the databases and plotted against the observed stock

Table 1. Summary of the main characteristics of the data used: The first three are databases using field measured data as the basis for the calculations, yet using different gap filling and calculation/mapping approaches, in order to estimate soil properties and cover maps at the global scale (SoilGrids and HWSD) and in high latitudes (NCSCD). The SoilGrids and HWSD data were aggregated to 0.5° (using a linear interpolation), the classical resolution used for land surface models running at global scale. The latter are the field data which consist of point measurements of carbon stocks based on stratified sampling available within the ISCN (global scale), the NSI (England and Wales) and the RMQS (France).

	Scale	**Initial grid resolution**	**Resolution after aggregation**	**Maximum depth**	**Number of layers**	**Data type**
SoilGrids	Global	5 km	0.5°	2 m	6	Estimated
HWSD	Global	1 km	0.5°	1 m	2	Estimated
NCSCD	High Latitudes	0.5°	-	3 m	4	Estimated
ISCN	Global	Not regular	-	1 m	1	Measured
RMQS	France	16 km^2	-	0.50 m	1	Measured
NSI	England and Wales	5 km^2	-	0.95 m	1	Measured

Table 2. Total organic carbon stock for the [0; 1 m] upper soil layer at the global and regional scales. Values are for the SoilGrids, HWSD and NCSCD databases; Bold numbers (percentage) are for the regional distribution of the global carbon stock.

		SoilGrids	**HWSD_SOTWIS**	**HWSD_SAXTON**	**NCSCD**
Carbon Stock (Pg C)	Global	3421	2439	2798	
	Boreal (60°N - 90°N)	1161	390	807	290
		34%	**16%**	**29%**	
	North Temperate (30°N - 60°N)	1376	890	1227	
		40%	**37%**	**44%**	
	Tropical (30°S - 30°N)	865	1061	696.6	
		25%	**44%**	**25%**	

Table3. Possible correlation between soil organic carbon stock (kg m^{-2}) of a given prodcut and soil properties, for the [0; 1 m] upper soil layer of the same product: The table gathers the slopes, the intercept and the R^2 coefficient obtained from the graphs of carbon stock according to the different properties of the soil (texture, pH and cation-exchange capacity (CEC)) on 1 m depth. It has been done for SoilGrids and the both products of HWSD, using SOTWIS and SAXTON bulk density.

	Clay content (%)			**Sand content (%)**			**Silt content (%)**			**CEC**			**pH**		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
SoilGrids	-0.20	34	<0.01	-0.07	52	0.04	0.20	21	0.05	0.09	13	0.01	-0.01	7	0.2
HWSD_SOTWIS	-0.75	45	<0.01	-0.06	22	<0.01	0.25	13	0.08	0.10	15	0.03	-1.90	32	<0.01
HWSD_SAXTON	-0.67	41	<0.01	-0.05	28	<0.01	0.31	23	0.03	0.28	14	0.02	-1.24	33	<0.01

Table 4: Possible trends between the ratio SOC/SOC_mean and climate for each grid cells: The table gathers the slopes, the intercept and the R^2 coefficient obtained from the graphs of carbon stock on 1 m depth according to the rainfall (kg m^{-2} s^{-1}) and air temperature (°C). It has been done for SoilGrids and the two products of HWSD using SOTWIS and SAXTON bulk density.

	Rainfall (kg m^{-2} s^{-1})			**Air temperature at 2 m (°C)**		
	Slope	Intercept	R^2	Slope	Intercept	R^2
SoilGrids	-7208	1	0.02	-0.06	2	0.3
HWSD_SOTWIS	-4891	1	0.02	-0.02	1	0.1
HWSD_SAXTON	-8194	1	0.01	-0.05	2	0.1

Table 5: NPP (kg m^{-2}) vs SOC (kg m^{-2}) per region: Relationship using NPP predicted by MODIS and the SOC stock established at regional scale. The table gathers the slopes, the intercept and the R^2 coefficient obtained from the graphs of carbon stock on 1 m depth according to the NPP, at regional scale. It has been done for SoilGrids and the both products of HWSD using SOTWIS and SAXTON bulk density.

	NPP_Boreal (kg m^{-2})			**NPP_Temperate (kg m^{-2})**			**NPP_Tropical (kg m^{-2})**		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
SoilGrids	165	42	0.2	11	38	0.03	22	4	0.2
HWSD_SOTWIS	103	2	0.01	13	17	0.07	14	9	0.2
HWSD_SAXTON	201	16	0.2	15	28	0.01	10	6	0.04

Figure 1. Global distribution of carbon stock on the [0;1 m] upper layer in the global scale (kg C m^{-2}) and for the different databases

Figure 2. The total carbon stock (kg C m^{-2}) on the [0;1 m] upper layer per latitude and for the different databases

Figure 3. The carbon profiles (Kg C m^{-3}) on the global and regional scales; the symbol is located at the lower depth of the corresponding layer

Figure 4. Global distribution of organic carbon concentration (kg/100 kg): Difference between SoilGrids and HWSD on the [0;1 m] upper layer

Figure 5. Global distribution of bulk density (kg m^{-3}): Difference between SoilGrids and HWSD on the [0;1 m] upper layer

Figure 6. Datasets comparison: For every location that corresponds to an analyzed soil profile recorded in the field databases, the corresponding carbon stock was estimated from the databases and plotted against the observed stock

Figure 1.

Global distribution of carbon stock on [0;1 m] (kg C m^{-2})

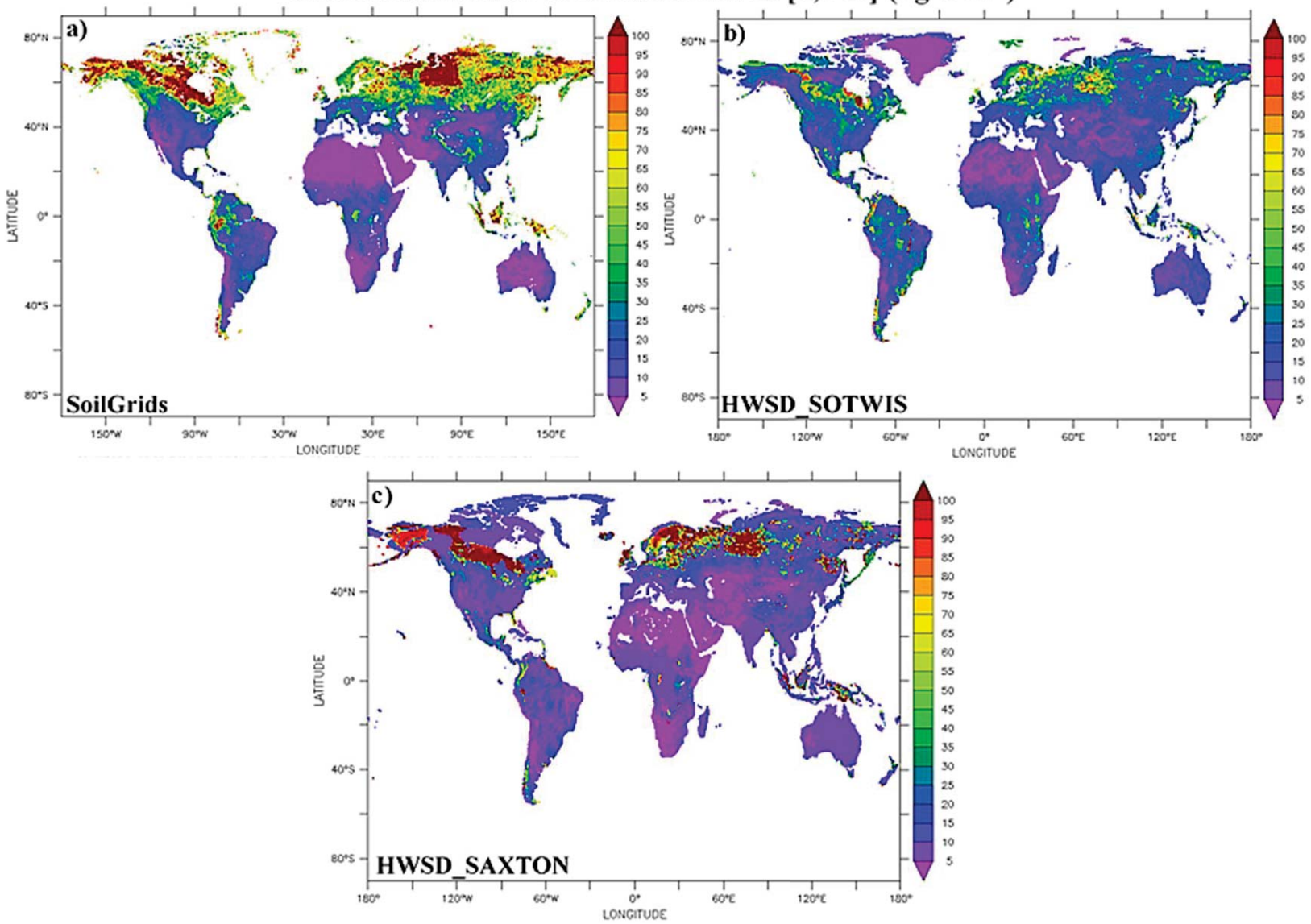


Figure 2.

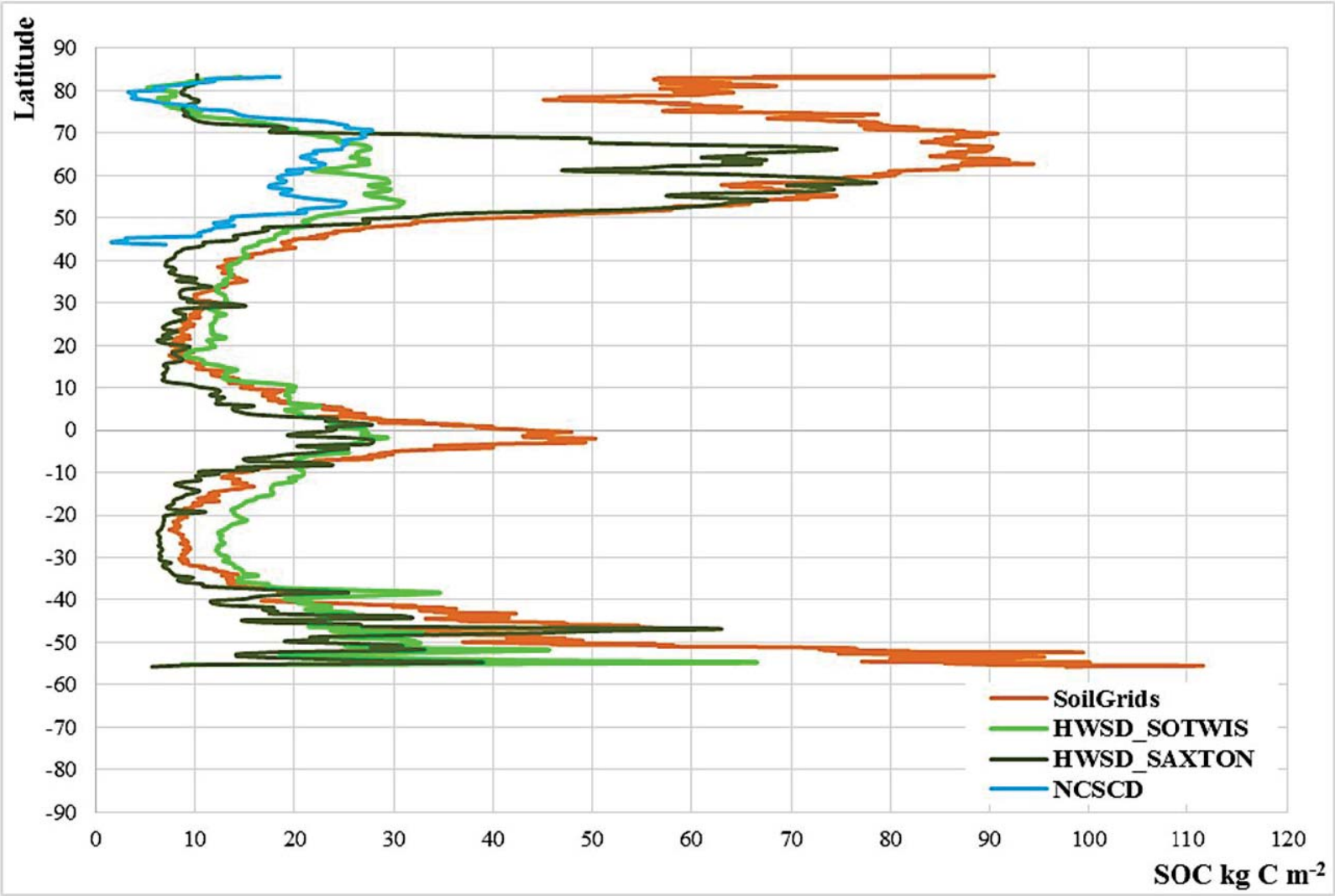
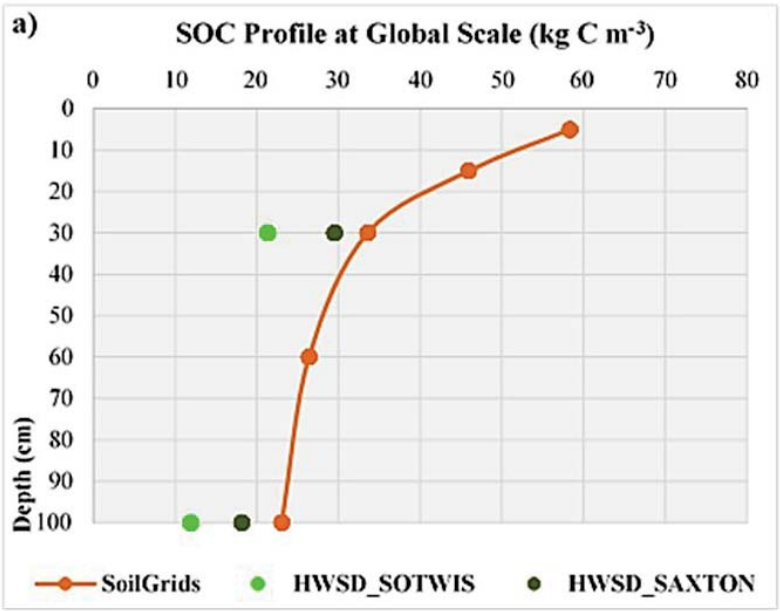
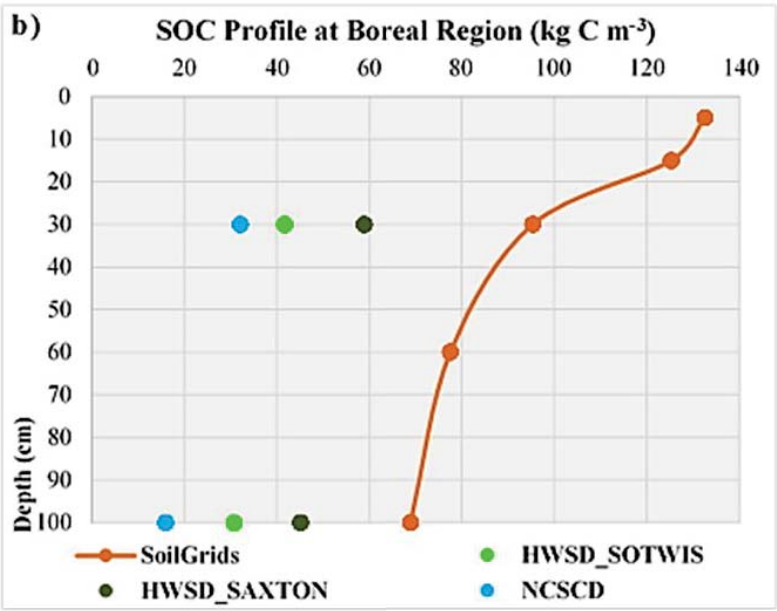
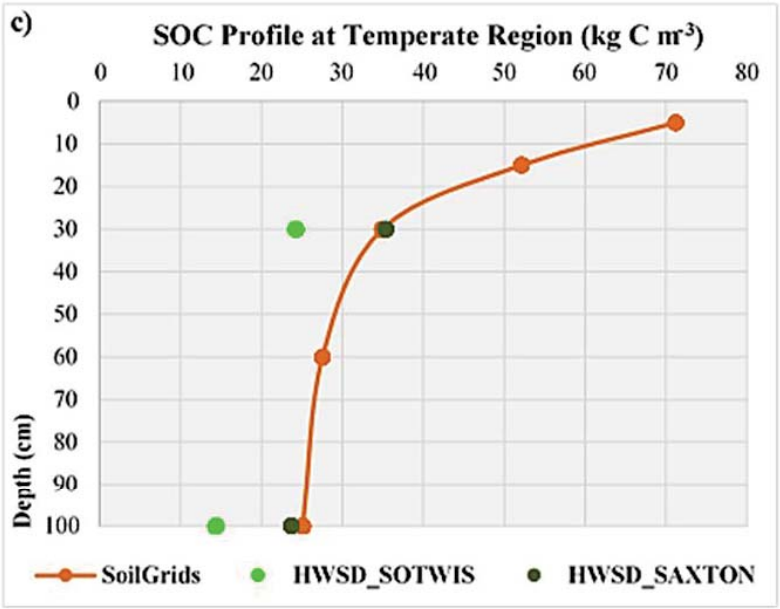

Latitude
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0
10
20
30
40
50
60
70
80
90
100
110
120
SOC kg C m-2
SoilGrids
HWSD_SOTWIS
HWSD_SAXTON
NCSCD

Figure 3.


a)
SOC Profile at Global Scale (kg C m-3)
0 10 20 30 40 50 60 70 80
Depth (cm)
0 10 20 30 40 50 60 70 80 90 100
SoilGrids
HWSD_SOTWIS
HWSD_SAXTON


b)
SOC Profile at Boreal Region (kg C m-3)
0 20 40 60 80 100 120 140
Depth (cm)
0 10 20 30 40 50 60 70 80 90 100
SoilGrids
HWSD_SOTWIS
HWSD_SAXTON
NCSCD


c)
SOC Profile at Temperate Region (kg C m-3)
0 10 20 30 40 50 60 70 80
Depth (cm)
0 10 20 30 40 50 60 70 80 90 100
SoilGrids
HWSD_SOTWIS
HWSD_SAXTON

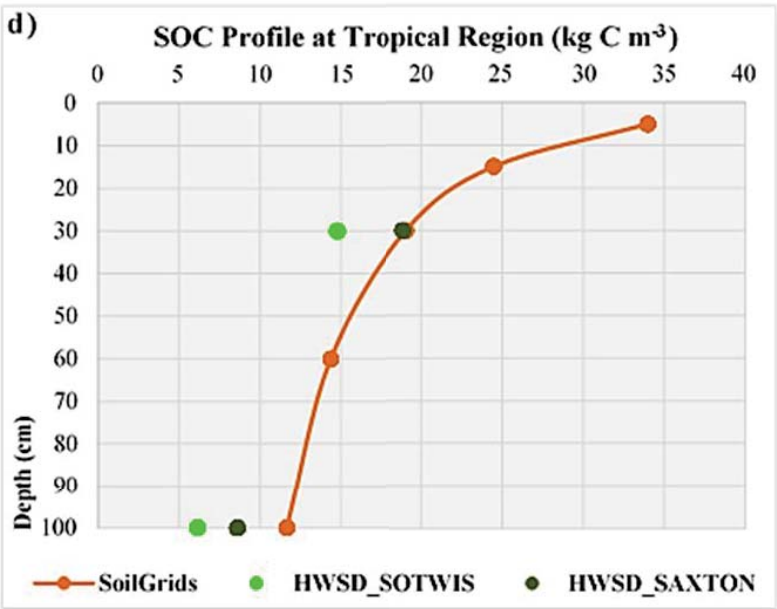

d)
SOC Profile at Tropical Region (kg C m-3)
0 5 10 15 20 25 30 35 40
Depth (cm)
0 10 20 30 40 50 60 70 80 90 100
SoilGrids
HWSD_SOTWIS
HWSD_SAXTON

Figure 4.

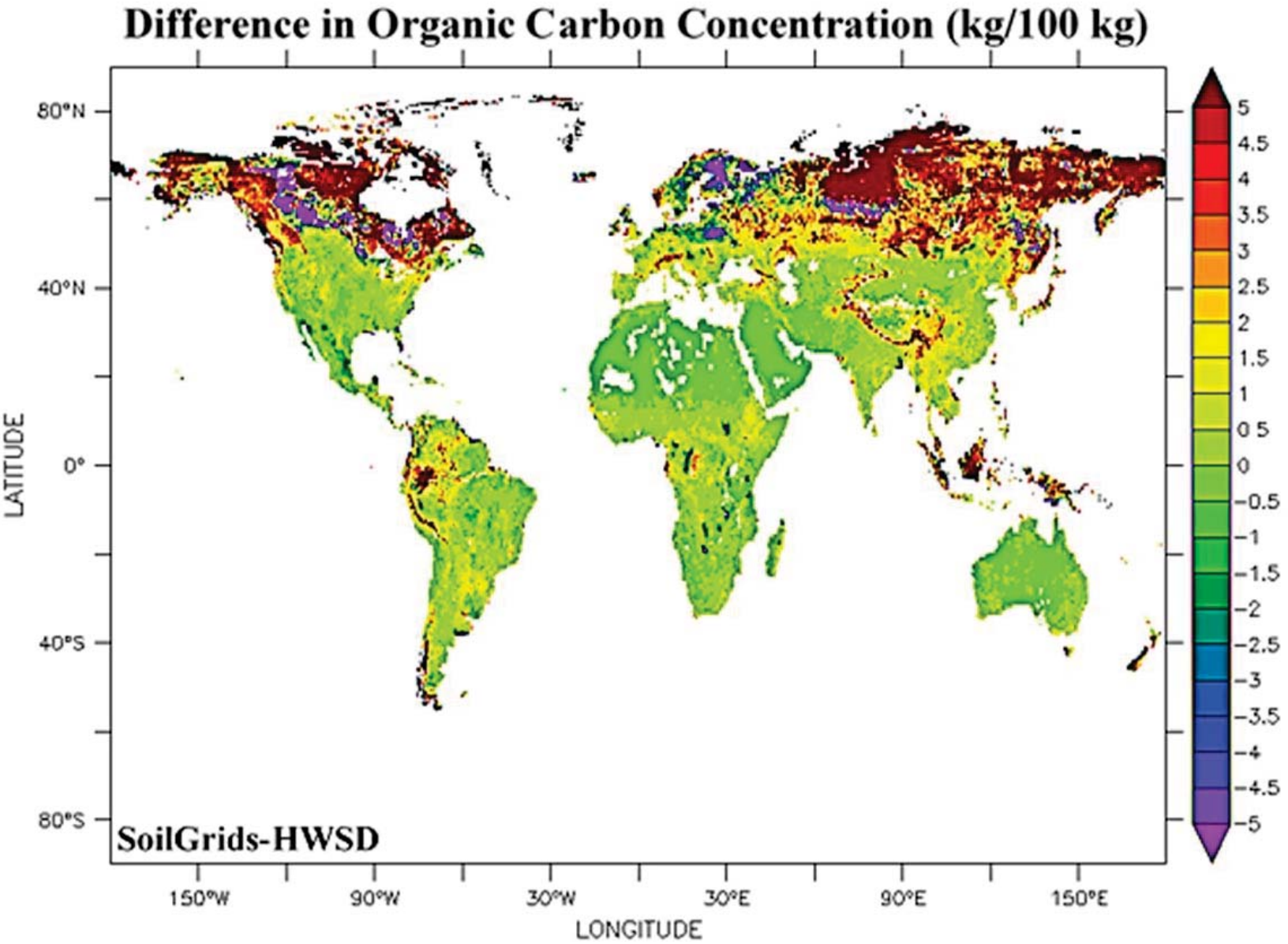

Difference in Organic Carbon Concentration (kg/100 kg)
80°N
40°N
0°
40°S
80°S
LATITUDE
150°W
90°W
30°W
30°E
90°E
150°E
LONGITUDE
SoilGrids-HWSD
5
4.5
4
3.5
3
2.5
2
1.5
1
0 5
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
−4.5
−5

Figure 5.

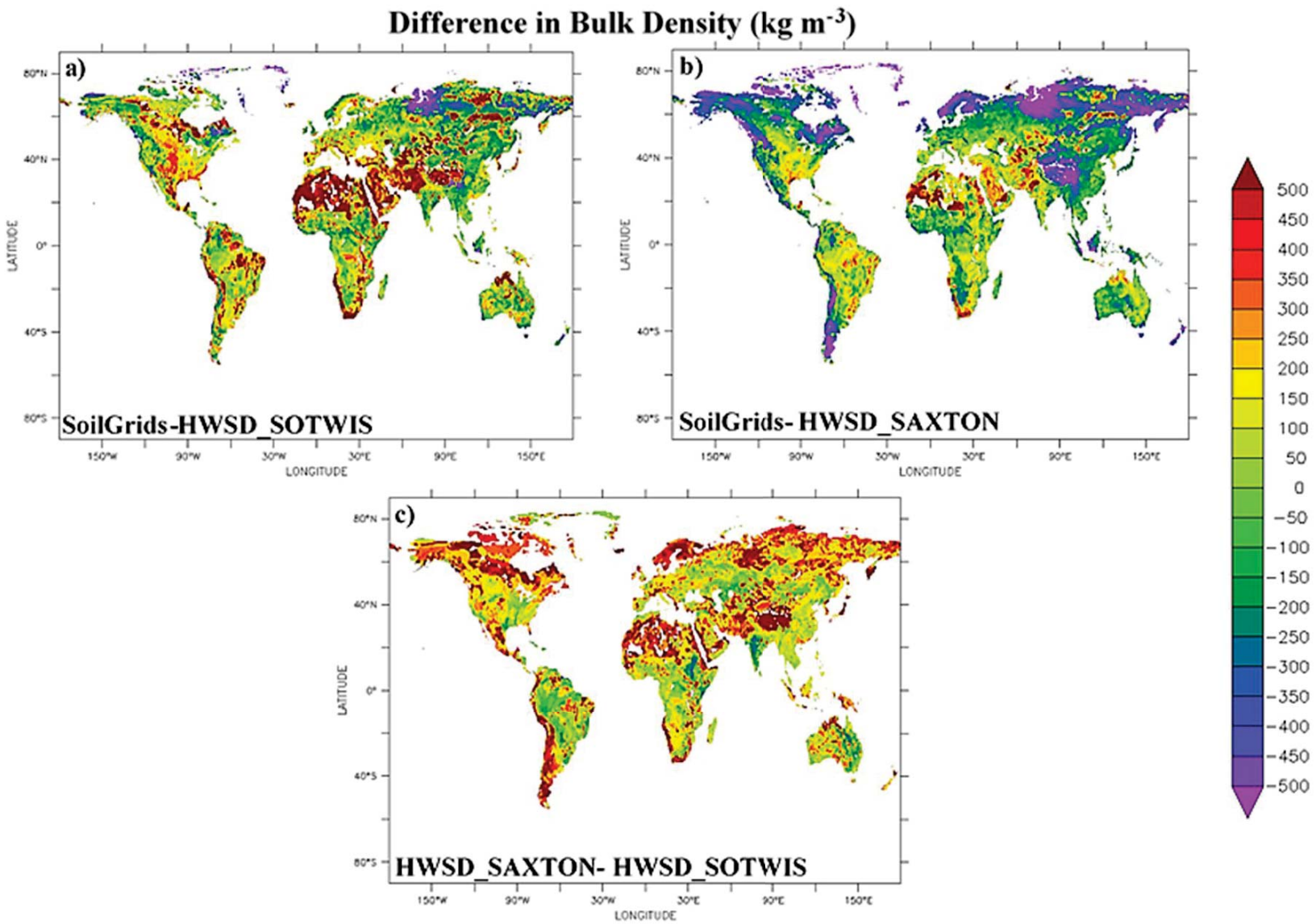
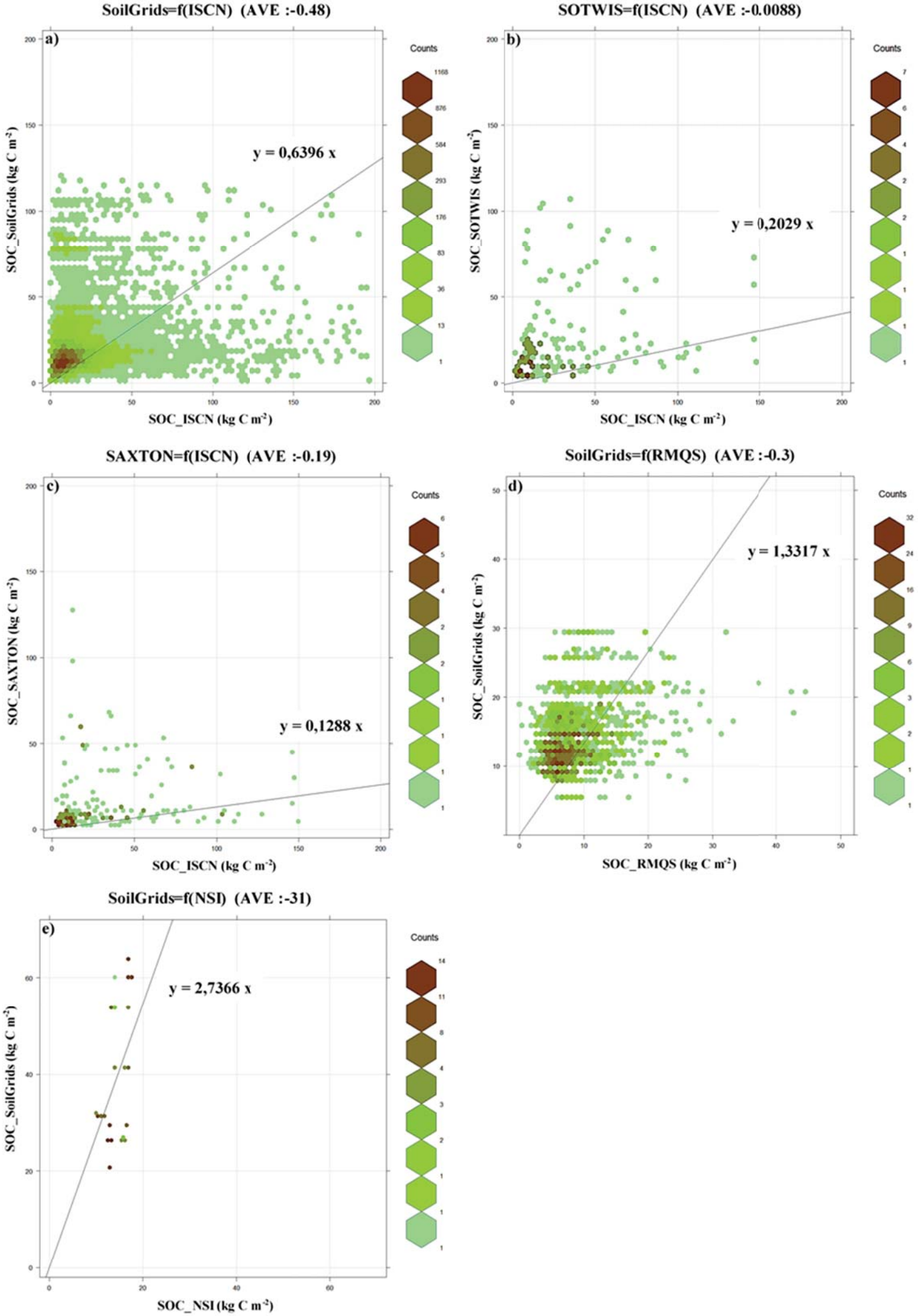

Difference in Bulk Density (kg m-3)
a)
SoilGrids-HWSD_SOTWIS
b)
SoilGrids- HWSD_SAXTON
c)
HWSD_SAXTON- HWSD_SOTWIS
LATITUDE
LONGITUDE
80°N
40°N
0°
40°S
80°S
150°W
90°W
30°W
30°E
90°E
150°E
500
450
400
350
300
250
200
150
100
50
0
−50
−100
−150
−200
−250
−300
−350
−400
−450
−500

Figure 6.


SoilGrids=f(ISCN) (AVE :-0.48)
a)
y = 0,6396 x
SOC_SoilGrids (kg C m-2)
SOC_ISCN (kg C m-2)
Counts
SOTWIS=f(ISCN) (AVE :-0.0088)
b)
y = 0,2029 x
SOC_SOTWIS (kg C m-2)
SOC_ISCN (kg C m-2)
Counts
SAXTON=f(ISCN) (AVE :-0.19)
c)
y = 0,1288 x
SOC_SAXTON (kg C m-2)
SOC_ISCN (kg C m-2)
Counts
SoilGrids=f(RMQS) (AVE :-0.3)
d)
y = 1,3317 x
SOC_SoilGrids (kg C m-2)
SOC_RMQS (kg C m-2)
Counts
SoilGrids=f(NSI) (AVE :-31)
e)
y = 2,7366 x
SOC_SoilGrids (kg C m-2)
SOC_NSI (kg C m-2)
Counts