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

4
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12

13 **Key points:**

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

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

52 The aim of our work is to compare soil organic carbon stocks given by different global and
53 regional databases that already exist. We calculated global and regional soil carbon stocks at
54 1m depth given by three existing databases (SoilGrids, the Harmonized World Soil Database,
55 and the Northern Circumpolar Soil Carbon Database). We observed that total stocks predicted
56 by each product differ greatly: it's estimated to be around 3400 Pg by SoilGrids and is about
57 2500 Pg according to HWSD. This difference is marked in particular for boreal regions where
58 differences can be related to high disparities in soil organic carbon concentration. Differences
59 in other regions are more limited and may be related to differences in bulk density estimates.
60 Finally, evaluation of the three datasets vs ground truth data shows that i) there is a significant
61 difference in spatial patterns between ground truth data and compared datasets and that ii)
62 datasets underestimate by more than 40% the soil organic carbon stock compared to field
63 data.

64

65 **Index terms and keywords**

66 0428, 0434, 0486

67 Soil, Organic carbon, uncertainties, bulk density, datasets

68

69 **1 Introduction**

70 Climate change is “unprecedented with respect to scale, severity and complexity” [*Bäckstrand*
71 *and Lövbrand, 2015*]. There has been a drastic increase in the atmospheric concentration of
72 carbon dioxide (and of other greenhouse gases) since the industrial revolution. This increase
73 in atmospheric CO₂ concentration is estimated to be about 31% since 1750 [*Lal, 2004b*], from
74 the combustion of fossil fuel (405±20 Pg, [*Quéré et al., 2015*]) and land use changes (190±65
75 Pg, [*Quéré et al., 2015*]). Thus there is an urgent need to understand the major role of carbon
76 with respect to climate change and therefore the short and long-term behavior of its various
77 compartments. Within this framework, the global carbon cycle is typically composed by three
78 large reservoirs interconnected through interchange pathways: the atmosphere, the terrestrial
79 biosphere and the ocean. The carbon exchanges among reservoirs are the result of different
80 chemical, physical and biological processes. Some stocks and flows among these reservoirs
81 are relatively well quantified. For instance, about 120 Pg C yr⁻¹ of atmospheric CO₂ is fixed
82 by terrestrial biomass via photosynthesis [*Janzen, 2004*]. In parallel, the flux of CO₂ to the
83 atmosphere from land use change was about 1.6 (0.5 to 2.7) Pg C yr⁻¹ for the 1990s [*Denman*
84 *et al., 2007*]. However, there is still much debate about the carbon stored in terrestrial
85 ecosystems [*Van der Werf G.D et al., 2009; Harris et al., 2012; Sanderman et al., 2017*] and
86 in particular in soils [*Köchy et al., 2015*]. While the ocean constitutes the largest active carbon
87 pool (including organic and inorganic carbon), soils are a major component of the terrestrial
88 ecosystem and the largest organic carbon reservoir on Earth. However, large knowledge gaps

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

91 The global mass of soil organic carbon is greater than the combined mass of carbon contained
92 in the atmosphere and in living biomass [Ciais *et al.*, 2013]. Soils contain 3.3 times the size of
93 the atmospheric carbon pool and 4.5 times the size of the biotic carbon pool [Lal, 2004a]. In
94 addition, soil is a non-renewable natural resource and is quite reactive to human disturbance
95 and climate change. Even minor changes in global soil organic carbon (SOC) mass may have
96 pronounced effects on atmospheric CO₂ concentrations and thus on climate change [Jones *et al.*,
97 2005; Schuur *et al.*, 2008]. Therefore, a better understanding of soil organic carbon stock
98 and flows is essential for better carbon management and climate change mitigation policies,
99 and also to help parameterize global circulation models used to guide climate policy.
100 Unfortunately, despite its importance, the global mass of SOC and its distribution in space are
101 not well known [Jandl *et al.*, 2014; Scharlemann *et al.*, 2014]. Although many estimates of
102 global [Amundson, 2001; Stockmann *et al.*, 2015] and regional [De Wit *et al.*, 2006; Tarnocai
103 *et al.*, 2009] SOC stocks have been published and the overall average value is generally
104 estimated to be around 1500 Pg [Batjes, 1996; Köchy *et al.*, 2015], this value tends to vary
105 considerably. A meta-analysis using 27 studies estimating global SOC mass by Scharlemann
106 *et al.* [2014] asserted that the median value of the estimated SOC mass is about 1460.5 Pg and
107 varies from 504 to 3000 Pg. This implies that, despite the large quantity of carbon stored as
108 soil organic carbon and despite a great deal of research, there remains substantial uncertainty
109 on the size of global SOC stocks and their spatial distribution [Scharlemann *et al.*, 2014]. This
110 may be explained by the numerous factors controlling SOC dynamics and all the associated
111 uncertainties as well as all the difficulties inherent in measuring and estimating carbon
112 concentrations and bulk density [Köchy *et al.*, 2015].

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

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

128

129 **2 Materials and methods**

130 Two types of data were used:

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

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

136 - Field data which consist of point measurements of carbon stocks on selected profiles
137 available within the International Soil Carbon Network (ISCN) [ISCN, 2012], the National
138 Survey Inventory of England and Wales (NSI) [Bellamy et al., 2005] and the Réseau de
139 Mesures de la Qualité des Sols of France (RMQS) [Arrouays et al., 2003; Jolivet et al., 2006]
140 .

141 In all cases, stocks are measured from the top of the mineral soil. For the datasets, the depth of
142 1 m was chosen in order to compare the products with each other (Table 1). Thereafter, to
143 compare the databases with the measurements, the stocks are compared on the same
144 minimum available depth. For instance, in the case of France, since the stock is supplied at a
145 depth of 50 cm, the comparison with the SoilGrids database was made taking into account the
146 stock at 50 cm depth only.

147

148 **2.1 Datasets estimating carbon stocks in soil**

149 **2.1.1 SoilGrids**

150 SoilGrids is a global soil information system containing spatial predictions for several soil
151 properties (clay, silt and sand content, pH index, cation-exchange capacity ...), at seven
152 standard depths: 0 cm, 5 cm, 15 cm, 30 cm, 60 cm, 100 cm and 200 cm [Hengl et al., 2014,
153 2017]. Altogether approximately 110,000 world soil profiles are used to generate this dataset.
154 The dataset (April 2017 version) can be downloaded here: <ftp://ftp.soilgrids.org/data/>. A
155 selection of the SoilGrids data is available as zipped datasets with a growing selection from
156 250 m to 10 km resolution. In this study, we used the 5 km resolution files (layers from 0 to
157 1m depth) which we aggregated to 0.5 degree resolution using a linear interpolation
158 (SoilGrids in tables and figures).

159 For SoilGrids, we first calculate the carbon content (OCC (wt %)), the bulk density (BD (kg
160 m⁻³)) and the gravel content (G (vol %)) for each standard layer (0-5 cm, 5-15 cm, 15-30 cm,
161 30-60 cm, 60-100 cm) as below, according to Hengl et al. [2017]:

$$162 \quad OCC_{a-b} = \frac{1}{2} \frac{1}{b-a} \sum (b-a)(OCC_a + OCC_b) \quad (1)$$

$$163 \quad BD_{a-b} = \frac{1}{2} \frac{1}{b-a} \sum (b-a)(BD_a + BD_b) \quad (2)$$

$$164 \quad G_{a-b} = \frac{1}{2} \frac{1}{b-a} \sum (b-a)(G_a + G_b) \quad (3)$$

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

166 Then, the soil organic carbon stock (SOC, (kg m⁻²)) was calculated, for each layer, using the
167 following equation:

$$168 \quad (SOC)_{a-b} = (OCC)_{a-b} * (BD)_{a-b} * (1 - G_{a-b}) * D_{a-b} \quad (4)$$

169 Where D is the layer thickness (m).

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

171

172 **2.1.2 Harmonized World Soil Database (HWSD)**

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

177 HWSD database provides soil properties for the topsoil (0 cm to 30 cm) and the subsoil (from
178 30 cm to 100 cm depth) layers only.

179 Soil organic carbon stock (SOC, (kg m⁻²)) was calculated, for each layer, using the following
180 equation:

$$181 \quad (SOC)_{0-30 \text{ cm}} = (OCC)_{0-30 \text{ cm}} * (BD)_{0-30 \text{ cm}} * (1 - G_{0-30 \text{ cm}}) * D_{0-30 \text{ cm}} \quad (5)$$

$$182 \quad (SOC)_{30-100 \text{ cm}} = (OCC)_{30-100 \text{ cm}} * (BD)_{30-100 \text{ cm}} * (1 - G_{30-100 \text{ cm}}) * D_{30-100 \text{ cm}} \quad (6)$$

183 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).

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

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

197

198 **2.1.3 Northern Circumpolar Soil Carbon Database (NCSCD)**

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

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

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

209

210 **2.2 Field data for soil Carbon stocks**

211 **2.2.1 International Soil Carbon Network (ISCN)**

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

214 America. The 1m soil stock provided (30,691 points over the world and mainly in North of
215 America) is the sum of its component layers, which may have been sampled by horizon or
216 depth [Cleve *et al.*, 1993; Michaelson *et al.*, 1996; Bockheim *et al.*, 1998, 1999, 2001, 2003,
217 2004; Jorgenson, 2000; Johnson *et al.*, 2003; Kristen *et al.*, 2004; Kane *et al.*, 2005; Neff *et al.*,
218 *et al.*, 2005; Ping *et al.*, 2005; Harden *et al.*, 2006; Myers-Smith *et al.*, 2007; Schuur *et al.*,
219 2007; Jorgenson *et al.*, 2008, 2009; Vogel *et al.*, 2008; Kane and Vogel, 2009; Boby *et al.*,
220 2010; Ping and Michaelson, 2010; O'Donnell *et al.*, 2011; Yarie and LTER, 2014]. The
221 dataset can be downloaded at <http://iscn.fluxdata.org/>.

222

223 **2.2.2 Network of Soil Quality Measurements (RMQS)**

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

229

230 **2.2.3 National Soil Inventory of England and Wales (NSI)**

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

235

236 **2.3 Soil Properties, Net Primary Productivity (NPP) and climate data**

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

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

256 running at global scale).

257

258 **3 Results**

259 **3.1 Latitudinal distribution of the global soil carbon stock on 1 m depth**

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

266 The major difference between the databases is observed at high latitudes (Figure 2); between
267 60°N and 90°N, the latitudinal profile shows a significant peak for SoilGrids and a slightly
268 less marked peak for HWSD_SAXTON. Yet this peak is less important in the case of
269 HWSD_SOTWIS and even lower with NCSCD. Between 50°N and 50°S, we note that the
270 curve of SoilGrids and that of HWSD are closer. Finally, SoilGrids again shows an important
271 peak, followed in this case by HWSD_SOTWIS.

272

273 **3.2 The stocks estimated by each product on 1 m depth**

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

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

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

293

294 **3.3 The SOC distribution within depth (up to 1 m deep)**

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

299 soil.

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

305

306 **3.4 Identifying sources of discrepancies**

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

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

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

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

328

329 **3.5 Benchmark using field measurements**

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

336 At the global scale (Figure 6a, 6b, 6c), all the products estimating SOC (SoilGrids,
337 HWSD_SOTWIS and HWSD_SAXTON) provide lower stocks than expected from field
338 measurements (compared to ISCN). Indeed, the slopes of the scatter plots vary from 0.1 to
339 0.6. However, SoilGrids is the closest to the measurements with a slope very close to 1 (0.6).

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

342 2.7, respectively.

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

345

346 **3.6 Driving factors for SOC stocks**

347 Table 3 gathers the slopes obtained for HWSD and SoilGrids from the graphs of carbon stock
348 according to the different properties of the soil (texture, pH and CEC) on 1 m depth. The table
349 presents the results of possible correlation of carbon stock to different soil properties: clay
350 content, silt content, sand content, pH or CEC. Overall, both databases show the same trends:
351 negative slopes for clay, sand and pH and positive slopes for silt and CEC. R^2 is quite low in
352 all cases, while the slopes are almost equal in absolute value. For example, the values for clay
353 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.

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

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

366

367 **4. Discussion**

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

375 SOC mass is a product of several factors (e.g. organic carbon concentration, bulk density and
376 coarse fragments [*Poeplau et al.*, 2017]). Consequently, uncertainties and errors in
377 measurement and estimation in just one of the factors may affect the final SOC stock
378 calculation. Therefore, it is unsurprising to see wide variations in carbon stock estimates from
379 one database to another, and even within the same database when using different
380 measurement methods and different subdatasets. Understanding and quantifying sources of
381 this variability is key to estimating the soil carbon stock at the global scale, since the
382 probability of errors increases with increasing spatial scale [*Xu et al.*, 2016; *Zhang et al.*,
383 2016].

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

386 (3421 Pg) is high compared to previous studies [Batjes, 1996; Köchy *et al.*, 2015]. It is
387 therefore very likely that previous estimates of the total organic carbon stock have seriously
388 underestimated organic carbon stock in northern latitudes, peatlands and wetlands. This
389 suggests that the value of the total carbon stock provided by SoilGrids may be the closest one
390 to reality. In fact, when compared to field data (Figure 6), estimates of SoilGrids are very
391 close to measurements with slopes of 0.6 (at the global scale) and 1.3 (at the scale of France).

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

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

399 Temperate regions account for the major part of the total carbon stock (between 37% and
400 44%). This is no doubt related to the very high amount of overall landmass located at
401 temperate latitudes rather than to a higher capacity to store carbon; the temperate region
402 accounts for 2.5 times the area of the tropics and 3.5 times the boreal land surface. Thus,
403 relative to the surface, the boreal region stores a very high amount of carbon mainly because
404 of the presence of permafrost and wetlands.

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

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

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

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

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

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

434 Nevertheless, some common factors between the databases may be identified. For instance,
435 SOC stock might be related to different soil properties (e.g. texture, pH, CEC) [Barré *et al.*,
436 2017], which obviously impact carbon decomposition rate in the soil. Looking at the results,
437 overall the trends are similar and slopes in absolute values are very close between the
438 databases.

439 Furthermore, SOC stocks are negatively correlated with temperature and precipitation. The
440 relation between soil temperature, moisture and SOC stocks is controlled by two factors. First,
441 the effect of plant primary production controlling the inputs and secondly the microbial
442 activity and the associated heterotrophic respiration controlling the outputs. Primary
443 production and microbial activity are both controlled by temperature and moisture [Piao *et al.*,
444 2006; Moyano *et al.*, 2012; Sierra, 2012] with non-linear interaction [Manzoni *et al.*,
445 2004]. Here the negative slopes observed suggest that climate effect on inputs are less than
446 those on outputs since precipitation and temperature stimulate the decomposition of organic
447 matter. Some tendencies (SOC according to climate, pH, etc.) are therefore similar between
448 datasets but the slopes of the relationship are often not.

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

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

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

485

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487

488 **5. Conclusion**

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

501

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- 519 1. Amundson, R. (2001), The carbon budget in soils, *Annu. Rev. Earth Planet Sci.*,
520 29(Houghton 1995), 535–562, doi:10.1146/annurev.earth.29.1.535.
- 521 2. Arora, V. K., and G. J. Boer (2014), Terrestrial ecosystems response to future changes
522 in climate and atmospheric CO₂ concentration, *Biogeosciences Discuss.*, 11(3), 3581–
523 3614, doi:10.5194/bgd-11-3581-2014.
- 524 3. Arora, V. K. et al. (2013), Carbon-concentration and carbon-climate feedbacks in
525 CMIP5 earth system models, *J. Clim.*, 26(15), 5289–5314, doi:10.1175/JCLI-D-12-
526 00494.1.
- 527 4. Arrouays, D., C. Jolivet, L. Boulonne, G. Bodineau, C. Ratié, N. Saby, and E.
528 Grolleau (2003), Le Réseau de Mesures de la Qualité des Sols de France
529 (RMQS). Etude et Gestion des Sols, 10 (4), 241-250.
530 <http://prodinra.inra.fr/record/69147>.
- 531 5. Bäckstrand, K., and E. Lövbrand (2015), Research handbook on climate governance.
532 Social and political sciences subject collection, Elgar publishing in UK and
533 USA. <http://dx.doi.org/10.4337/9781783470600.00036>
- 534 6. Barré, P., H. Durand, C. Chenu, P. Meunier, D. Montagne, G. Castel, D. Billiou, L.
535 Soucémarianadin, and L. Cécillon (2017), Geological control of soil organic carbon
536 and nitrogen stocks at the landscape scale, *Geoderma*, 285, 50–56,
537 doi:10.1016/j.geoderma.2016.09.029.
- 538 7. Batjes, N. H. (1996), Total carbon and nitrogen in the soils of the world, *Eur. J. Soil*
539 *Sci.*, 47(2), 151–163, doi:10.1111/j.1365-2389.1996.tb01386.x.
- 540 8. Batjes, N. H. (2016), Harmonized soil property values for broad-scale modelling
541 (WISE30sec) with estimates of global soil carbon stocks, *Geoderma*, 269, 61–68,
542 doi:10.1016/j.geoderma.2016.01.034.
- 543 9. Bellamy, P. H., P. J. Loveland, R. I. Bradley, R. M. Lark, and G. J. D. Kirk (2005),
544 Carbon losses from all soils across England and Wales 1978-2003, *Nature*,
545 437(September), 245–248, doi:10.1038/nature04038.
- 546 10. Boby, L. A., E. A. G. Schuur, M. C. Mack, D. Verbyla, and J. F. Johnstone (2010),
547 Quantifying fire severity, carbon, and nitrogen emissions in Alaska’s boreal forest,
548 *Ecol. Appl.*, 20(6), 1633–1647, doi:10.1890/08-2295.1.
- 549 11. Bockheim, J. G., D. A. Walker, L. R. Everett, F. E. Nelson, and N. I. Shiklomanov
550 (1998), Soils and Cryoturbation in Moist Nonacidic and Acidic Tundra in the Kuparuk
551 River Basin, Arctic Alaska, U.S.A., *Arct. Alp. Res.*, 30(2), 166, doi:10.2307/1552131.
- 552 12. Bockheim, J. G., L. R. Everett, K. M. Hinkel, F. E. Nelson, and J. Brown (1999), Soil
553 Organic Carbon Storage and Distribution in Arctic Tundra, Barrow, Alaska, *Soil Sci.*
554 *Soc. Am. J.*, 63(4), 934, doi:10.2136/sssaj1999.634934x.
- 555 13. Bockheim, J. G., K. M. Hinkel, and F. E. Nelson (2001), Soils of the Barrow region,
556 Alaska¹, *Polar Geogr.*, 25(3), 163–181, doi:10.1080/10889370109377711.
- 557 14. Bockheim, J. G., K. M. Hinkel, and F. E. Nelson (2003), Predicting Carbon Storage in
558 Tundra Soils of Arctic Alaska, *Soil Sci. Soc. Am. J.*, 67(3), 948–950,
559 doi:10.2136/SSSAJ2003.9480.

- 560 15. Bockheim, J. G., K. M. Hinkel, W. R. Eisner, and X. Y. Dai (2004), Carbon Pools and
561 Accumulation Rates in an Age-Series of Soils in Drained Thaw-Lake Basins, Arctic
562 Alaska, *Soil Sci. Soc. Am. J.*, 68(2), 697–704, doi:10.2136/sssaj2004.0697.
- 563 16. Botula, Y. D., A. Nemes, E. Van Ranst, P. Mafuka, J. De Pue, and W. M. Cornelis
564 (2015), Hierarchical Pedotransfer Functions to Predict Bulk Density of Highly
565 Weathered Soils in Central Africa, *Soil Sci. Soc. Am. J.*, 79(2), 476–486, doi:DOI
566 10.2136/sssaj2014.06.0238.
- 567 17. Carvalhais, N. et al. (2014), Global covariation of carbon turnover times with climate
568 in terrestrial ecosystems, *Nature*, 514, 213–217, doi:10.1038/nature13731.
- 569 18. Ciais, P. et al. (2013), Carbon and Other Biogeochemical Cycles, *Clim. Chang. 2013 -*
570 *Phys. Sci. Basis*, 465–570, doi:10.1017/CBO9781107415324.015.
- 571 19. Cleve, K. Van, C. T. Dyrness, G. M. Marion, and R. Erickson (1993), Control of soil
572 development on the Tanana River floodplain, interior Alaska, *Can. J. For. Res.*, 23(5),
573 941–955, doi:10.1139/x93-122.
- 574 20. Compo, G. P. et al. (2011), The Twentieth Century Reanalysis Project, *Q. J. R.*
575 *Meteorol. Soc.*, 137(654), 1–28, doi:10.1002/qj.776.
- 576 21. Davidson, E. A., and I. A. Janssens (2006), Temperature sensitivity of soil carbon
577 decomposition and feedbacks to climate change., *Nature*, 440(March), 165–173,
578 doi:10.1038/nature04514.
- 579 22. Denman, K. L., G. Brasseur, A. Chidthaisong, P. Ciais, P. M. Cox, R. E. Dickinson,
580 D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P.
581 L. da Silva Dias, S. C. Wofsy, and X. Zhang (2007), Couplings Between Changes in
582 the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical*
583 *Science Basis. Contribution of Working Group I to the Fourth Assessment Report of*
584 *the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning,
585 Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge
586 University Press, Cambridge, United Kingdom and New York, NY, USA.
- 587 23. Doetterl, S. et al. (2015), Soil carbon storage controlled by interactions between
588 geochemistry and climate, *Nat. Geosci.*, 8(10), 780–783, doi:10.1038/NGEO2516.
- 589 24. FAO/IIASA/ISRIC/ISS-CAS/JRC (2012), Harmonized World Soil Database (version
590 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.
- 591 25. Generation 2 Database Reports: International Soil Carbon Network, 2012. Generation
592 2 Database Report: Carbonto1M_LATEST.xls. Accessed February 2015.
- 593 26. Harden, J. W., K. L. MANIES, M. R. TURETSKY, and J. C. NEFF (2006), Effects of
594 wildfire and permafrost on soil organic matter and soil climate in interior Alaska,
595 *Glob. Chang. Biol.*, 12(12), 2391–2403, doi:10.1111/j.1365-2486.2006.01255.x.
- 596 27. Harris, N., S. Brown, S. Hagen, A. Baccini, and R. Houghton (2012), *Progress toward*
597 *a consensus on carbon emissions from tropical deforestation*.
- 598 28. Hengl, T. et al. (2014), SoilGrids1km — Global Soil Information Based on Automated
599 Mapping, *PLoS One*, 9(8), e105992, doi:10.1371/journal.pone.0105992.
- 600 29. Hengl, T. et al. (2017), SoilGrids250m: Global gridded soil information based on
601 machine learning, edited by B. Bond-Lamberty, *PLoS One*, 12(2), e0169748,

- 602 doi:10.1371/journal.pone.0169748.
- 603 30. Heuscher, S. a, C. C. Brandt, and P. M. Jardine (2005), Using Soil Physical and
604 Chemical Properties to Estimate Bulk Density, *Soil Sci. Soc. Am. J.*, 69(1), 51–56,
605 doi:10.2136/sssaj2005.0051
- 606 31. Hiederer, R., Ramos, F., Capitani, C., Koeble, R., Blujdea, V., Gomez, O., Mulligan,
607 D., and Marelli, L.: Biofuels: a new methodology to estimate GHG emissions from
608 global land usechange, JRC Scientific and Technical Reports, EUR 24483 EN, Office
609 for Official Publications of the European Communities, Luxembourg, Office for
610 Official Publications of the EuropeanCommunities, doi:10.2788/48910, 2010.
- 611 32. Hugelius, G. et al. (2013a), A new data set for estimating organic carbon storage to 3
612 m depth in soils of the northern circumpolar permafrost region, *Earth Syst. Sci. Data*,
613 5(2), 393–402, doi:10.5194/essd-5-393-2013.
- 614 33. Hugelius, G., C. Tarnocai, G. Broll, J. G. Canadell, P. Kuhry, and D. K. Swanson
615 (2013b), The northern circumpolar soil carbon database: Spatially distributed datasets
616 of soil coverage and soil carbon storage in the northern permafrost regions, *Earth Syst.*
617 *Sci. Data*, 5(1), 3–13, doi:10.5194/essd-5-3-2013.
- 618 34. Jandl, R. et al. (2014), Current status, uncertainty and future needs in soil organic
619 carbon monitoring, *Sci. Total Environ.*, 468–469, 376–383,
620 doi:10.1016/j.scitotenv.2013.08.026.
- 621 35. Janzen, H. (2004), Carbon cycling in earth systems - A soil science perspective, *Agric.*
622 *Ecosyst. Environ.*, 104(3), 399–417, doi:10.1016/j.agee.2004.01.040.
- 623 36. Johnson, D. W., D. E. Todd, and V. R. Tolbert (2003), Changes in Ecosystem Carbon
624 and Nitrogen in a Loblolly Pine Plantation over the First 18 Years, *Soil Sci. Soc. Am.*
625 *J.*, 67, 1594–1601.
- 626 37. Jolivet, C., D. Arrouays, L. Boulonne, C. Ratié, and N. Saby. 2006. Le Réseau de
627 Mesures de la Qualité des Sols de France (RMQS). État d’avancement et premiers
628 résultats. *Étude et Gestion Sols* 13:149–164.
- 629 38. Jones, C., C. McConnell, K. Coleman, P. Cox, P. Falloon, D. Jenkinson, and D.
630 Powlson (2005), Global climate change and soil carbon stocks; predictions from two
631 contrasting models for the turnover of organic carbon in soil, *Glob. Chang. Biol.*,
632 11(1), 154–166, doi:10.1111/j.1365-2486.2004.00885.x.
- 633 39. Jorgenson, M. T. (2000), Hierarchical Organization of Ecosystems at Multiple Spatial
634 Scales on the Yukon-Kuskokwim Delta, Alaska, U.S.A., *Arctic, Antarct. Alp. Res.*,
635 32(3), 221, doi:10.2307/1552521.
- 636 40. Jorgenson, M. T., J. Roth, T. Miller, E. Pullman, T. Cater, M. Duffy, W. Davis, M.
637 Macander, and J. Grunblatt (2008), Ecological Land Classification and Mapping of the
638 Wrangell-St. Elias National Park and Preserve, *Nat. Resour. Tech. Report*,
639 *NPS/WRST/NRTR-2008/094. Natl. Park Serv. Anchorage, AK.*
- 640 41. Jorgenson, M. T., J. E. Roth, P. F. Miller, M. J. Macander, M. S. Duffy, A. F. Wells,
641 G. V. Frost, and E. R. Pullman (2009), An Ecological Land Survey and Landcover
642 Map of the Arctic Network, *An Ecol. L. Surv. Landcover Map Arct. Network. Natl.*
643 *Park Serv. CO, NPS/ARC/NRTR—2009/270. 307 p., 307.*

- 644 42. Kane, E. S., and J. G. Vogel (2009), Patterns of Total Ecosystem Carbon Storage with
645 Changes in Soil Temperature in Boreal Black Spruce Forests, *Ecosystems*, 12(2), 322–
646 335, doi:10.1007/s10021-008-9225-1.
- 647 43. Kane, E. S., D. W. Valentine, E. A. Schuur, and K. Dutta (2005), Soil carbon
648 stabilization along climate and stand productivity gradients in black spruce forests of
649 interior Alaska, *Can. J. For. Res.*, 35(9), 2118–2129, doi:10.1139/x05-093.
- 650 44. Köchy, M., R. Hiederer, and a. Freibauer (2015), Global distribution of soil organic
651 carbon – Part 1: Masses and frequency distributions of SOC stocks for the tropics,
652 permafrost regions, wetlands, and the world, *Soil*, 1(1), 351–365, doi:10.5194/soil-1-
653 351-2015.
- 654 45. Kristen, L., J. W. Harden, S. R. Silva, P. H. Briggs, and B. M. Schmid (2004), *Open-*
655 *file report*, U.S. Dept. of the Interior.
- 656 46. Lal, R. (2004a), Soil Carbon Sequestration Impacts on Global Climate Change and
657 Food Security, *Scienc*, 304(5677), 1623–1627, doi:10.1126/science.1097396.
- 658 47. Lal, R. (2004b), Soil carbon sequestration to mitigate climate change, *Geoderma*,
659 123(1–2), 1–22, doi:10.1016/j.geoderma.2004.01.032.
- 660 48. Lobsey, C. R., and R. A. Viscarra Rossel (2016), Sensing of soil bulk density for more
661 accurate carbon accounting, *Eur. J. Soil Sci.*, 67(4), 504–513, doi:10.1111/ejss.12355.
- 662 49. Luo, Y. et al. (2016), Toward more realistic projections of soil carbon dynamics by
663 Earth system models, *Global Biogeochem. Cycles*, 30(1), 40–56,
664 doi:10.1002/2015GB005239.
- 665 50. Manrique, L. a., and C. a. Jones (1991), Bulk Density of Soils in Relation to Soil
666 Physical and Chemical Properties, *Soil Sci. Soc. Am. J.*, 55(2), 476,
667 doi:10.2136/sssaj1991.03615995005500020030x.
- 668 51. Manzoni, S., a. Porporato, P. D’Odorico, F. Laio, and I. Rodriguez-Iturbe (2004), Soil
669 nutrient cycles as a nonlinear dynamical system, *Nonlinear Process. Geophys.*,
670 11(5/6), 589–598, doi:10.5194/npg-11-589-2004.
- 671 52. Martin, M. P., D. Lo Seen, L. Boulonne, C. Jolivet, K. M. Nair, G. Bourgeon, and D.
672 Arrouays (2009), Optimizing Pedotransfer Functions for Estimating Soil Bulk Density
673 Using Boosted Regression Trees, *Soil Sci. Soc. Am. J.*, 73(2), 485,
674 doi:10.2136/sssaj2007.0241.
- 675 53. Michaelson, G. J., C. L. Ping, and J. M. Kimble (1996), Carbon Storage and
676 Distribution in Tundra Soils of Arctic Alaska, U.S.A., *Arct. Alp. Res.*, 28(4), 414,
677 doi:10.2307/1551852.
- 678 54. Moyano, F. E. et al. (2012), The moisture response of soil heterotrophic respiration:
679 Interaction with soil properties, *Biogeosciences*, 9(3), 1173–1182, doi:10.5194/bg-9-
680 1173-2012.
- 681 55. Myers-Smith, I. H., A. D. McGuire, J. W. Harden, and F. S. Chapin (2007), Influence
682 of disturbance on carbon exchange in a permafrost collapse and adjacent burned
683 forest, *J. Geophys. Res. Biogeosciences*, 112(G4), n/a-n/a,
684 doi:10.1029/2007JG000423.
- 685 56. Neff, J. C., J. W. Harden, and G. Gleixner (2005), Fire effects on soil organic matter

- 686 content, composition, and nutrients in boreal interior Alaska, *Can. J. For. Res.*, 35(9),
687 2178–2187, doi:10.1139/x05-154.
- 688 57. Nishina, K. et al. (2014), Quantifying uncertainties in soil carbon responses to changes
689 in global mean temperature and precipitation, *Earth Syst. Dyn.*, 5(1), 197–209,
690 doi:10.5194/esd-5-197-2014.
- 691 58. O'Donnell, J. A., J. W. HARDEN, A. D. McGUIRE, M. Z. KANEVSKIY, M. T.
692 JORGENSON, and X. XU (2011), The effect of fire and permafrost interactions on
693 soil carbon accumulation in an upland black spruce ecosystem of interior Alaska:
694 implications for post-thaw carbon loss, *Glob. Chang. Biol.*, 17(3), 1461–1474,
695 doi:10.1111/j.1365-2486.2010.02358.x.
- 696 59. Piao, S., P. Friedlingstein, P. Ciais, L. Zhou, and A. Chen (2006), Effect of climate
697 and CO₂ changes on the greening of the Northern Hemisphere over the past two
698 decades, *Geophys. Res. Lett.*, 33(23), L23402, doi:10.1029/2006GL028205.
- 699 60. Ping, C. L., and G. J. Michaelson (2010), Carbon Stores and Biogeochemical
700 Properties of Soils under Black Spruce Forest, Alaska, *Soil Sci. Soc. Am. J.*, 74(3),
701 969, doi:10.2136/sssaj2009.0152.
- 702 61. Ping, C. L., G. J. Michaelson, E. C. Packee, C. A. Stiles, D. K. Swanson, and K.
703 Yoshikawa (2005), Soil Catena Sequences and Fire Ecology in the Boreal Forest of
704 Alaska, *Soil Sci. Soc. Am. J.*, 69(6), 1761, doi:10.2136/sssaj2004.0139.
- 705 62. Poeplau, C., C. Vos, and A. Don (2017), Soil organic carbon stocks are systematically
706 overestimated by misuse of the parameters bulk density and rock fragment content,
707 *SOIL*, 3(1), 61–66, doi:10.5194/soil-3-61-2017.
- 708 63. Quéré, C. Le et al. (2015), Global Carbon Budget 2015, *Earth Syst. Sci. Data*, 7(2),
709 349–396, doi:10.5194/essd-7-349-2015.
- 710 64. Saxton, K. E., W. J. Rawls, J. S. Romberger, and R. I. Papendick (1986), Estimating
711 Generalized Soil-water Characteristics from Texture. *Soil Science Society American*
712 *journal*, 50, 1031-1036. <https://doi:10.2136/sssaj1986.03615995005000040039x>
- 713 65. Sanderman, J., T. Hengl, and G. J. Fiske (2017), Soil carbon debt of 12,000 years of
714 human land use., *Proc. Natl. Acad. Sci. U. S. A.*, 114(36), 9575–9580,
715 doi:10.1073/pnas.1706103114.
- 716 66. Scharlemann, J. P., E. V. Tanner, R. Hiederer, and V. Kapos (2014), Global soil
717 carbon: understanding and managing the largest terrestrial carbon pool, *Carbon*
718 *Manag.*, 5(1), 81–91, doi:10.4155/CMT.13.77.
- 719 67. Schmidt, M. W. I. et al. (2011), Persistence of soil organic matter as an ecosystem
720 property, *Nature*, 478(7367), 49–56, doi:10.1038/nature10386.
- 721 68. Schuur, E. A. G., K. G. Crummer, J. G. Vogel, and M. C. Mack (2007), Plant Species
722 Composition and Productivity following Permafrost Thaw and Thermokarst in
723 Alaskan Tundra, *Ecosystems*, 10(2), 280–292, doi:10.1007/s10021-007-9024-0.
- 724 69. Schuur, E. a G. et al. (2008), Vulnerability of permafrost carbon to climate change:
725 Implications for the global carbon cycle, *Bioscience*, 58(8), 701–714,
726 doi:10.1641/B580807.
- 727 70. Sequeira, C. H., S. A. Wills, C. A. Seybold, and L. T. West (2014), Predicting soil

- 728 bulk density for incomplete databases, *Geoderma*, 213, 64–73,
729 doi:10.1016/j.geoderma.2013.07.013.
- 730 71. Sierra, C. A. (2012), Temperature sensitivity of organic matter decomposition in the
731 Arrhenius equation: Some theoretical considerations, *Biogeochemistry*, 108(1–3), 1–
732 15, doi:10.1007/s10533-011-9596-9.
- 733 72. Stockmann, U., J. Padarian, A. McBratney, B. Minasny, D. de Brogniez, L.
734 Montanarella, S. Y. Hong, B. G. Rawlins, and D. J. Field (2015), Global soil organic
735 carbon assessment, *Glob. Food Sec.*, 6, 9–16, doi:10.1016/j.gfs.2015.07.001.
- 736 73. Tarnocai, C., J. G. Canadell, E. A. G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov
737 (2009), Soil organic carbon pools in the northern circumpolar permafrost region,
738 *Global Biogeochem. Cycles*, 23(GB2023), doi:10.1029/2008GB003327,
739 doi:Gb2023\n10.1029/2008gb003327.
- 740 74. Todd-Brown, K. et al. (2014), Changes in soil organic carbon storage predicted by
741 Earth system models during the 21st century, *Biogeosciences*, 11, 2341–2356,
742 doi:10.5194/bg-11-2341-2014.
- 743 75. Vogel, J. G., B. P. BOND-LAMBERTY, E. A. G. SCHUUR, S. T. GOWER, M. C.
744 MACK, K. E. B. O’CONNELL, D. W. VALENTINE, and R. W. RUESS (2008),
745 Carbon allocation in boreal black spruce forests across regions varying in soil
746 temperature and precipitation, *Glob. Chang. Biol.*, 14(7), 1503–1516,
747 doi:10.1111/j.1365-2486.2008.01600.x.
- 748 76. Van der Werf G.D, D. C. Morton, R. S. DeFries, J. G. J. Olivier, and P. S. Kasibhatla
749 (2009), CO₂ emissions from forest loss, *Nat. Geosci.*, 2(11), 737–738,
750 doi:10.1038/ngeo671.
- 751 77. De Wit, H. A., T. Palosuo, G. Hylen, and J. Liski (2006), A carbon budget of forest
752 biomass and soils in southeast Norway calculated using a widely applicable method,
753 *For. Ecol. Manage.*, 225(1–3), 15–26, doi:10.1016/j.foreco.2005.12.023.
- 754 78. Xu, L., N. P. He, G. R. Yu, D. Wen, Y. Gao, and H. L. He (2015), Differences in
755 pedotransfer functions of bulk density lead to high uncertainty in soil organic carbon
756 estimation at regional scales: Evidence from Chinese terrestrial ecosystems, *J.
757 Geophys. Res. Biogeosciences*, 120(8), 1567–1575, doi:10.1002/2015JG002929.
- 758 79. Xu, L., N. He, and G. Yu (2016), Methods of evaluating soil bulk density: Impact on
759 estimating large scale soil organic carbon storage, *Catena*, 144, 94–101,
760 doi:10.1016/j.catena.2016.05.001.
- 761 80. Yarie, J., and B. C. LTER (2014), Soil physical and chemical properties based on
762 genetic horizon from 4 replicate pits placed around the replicate LTER control plots
763 sampled in 1988 and 1989., ,
764 doi:10.6073/PASTA/475A1825DFA264822ED53CA3574BB8E6.
- 765 81. Zhang, L., Q. Zhuang, Q. Zhao, Y. He, D. Yu, X. Shi, and S. Xing (2016), Uncertainty
766 of organic carbon dynamics in Tai-Lake paddy soils of China depends on the scale of
767 soil maps, *Agric. Ecosyst. Environ.*, 222, 13–22, doi:10.1016/j.agee.2016.01.049.
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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 ($\text{kg}/100 \text{ kg}$): 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
	Global	3421	2439	2798	
Carbon Stock (Pg C)	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 product 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 R² 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 R² 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

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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})

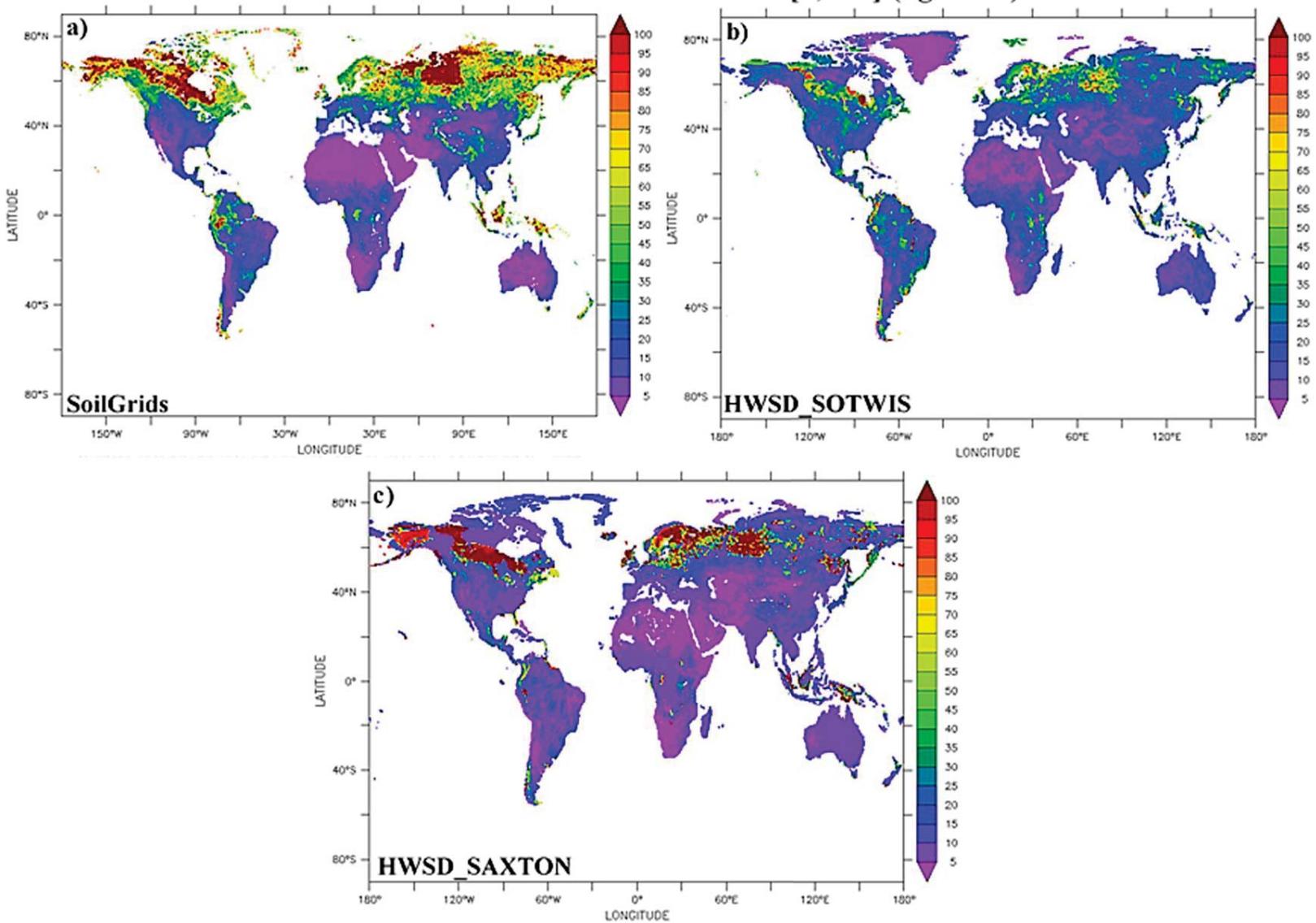


Figure 2.

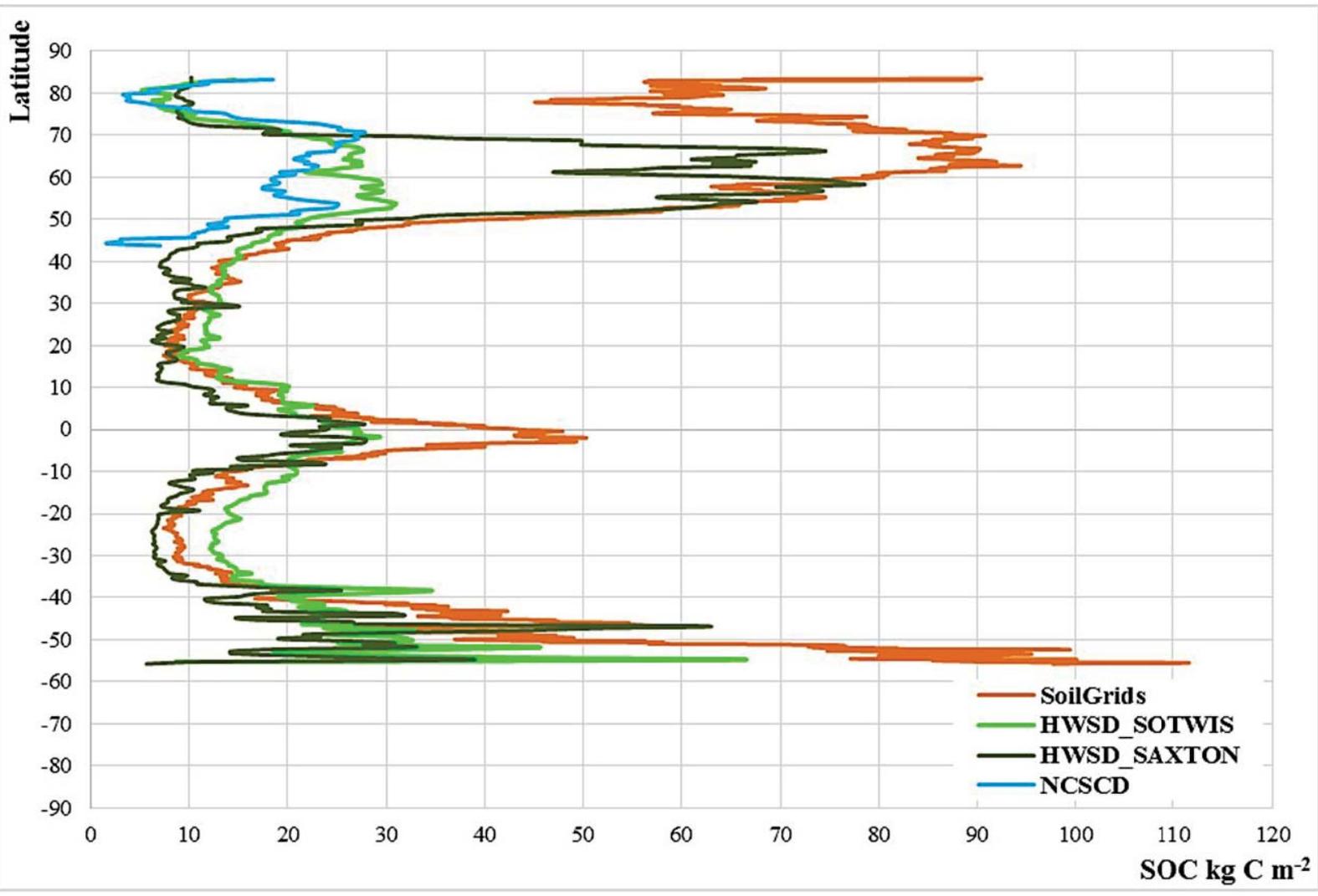


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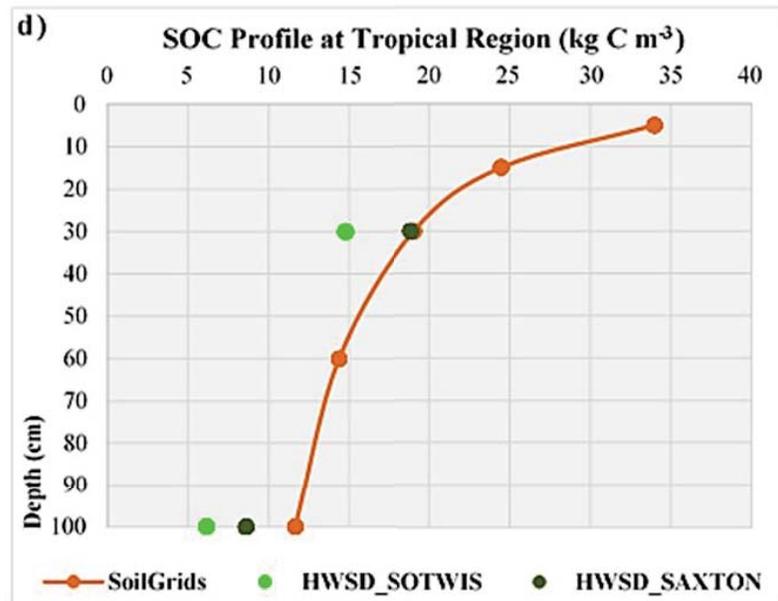
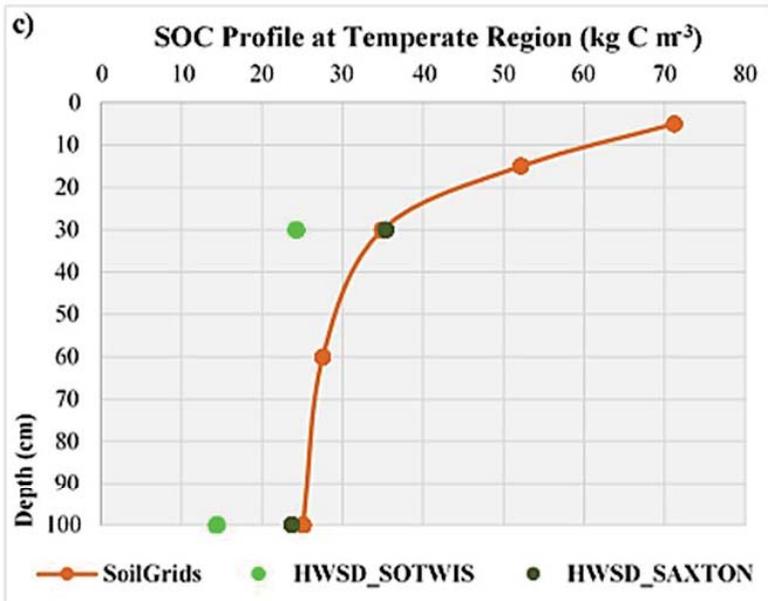
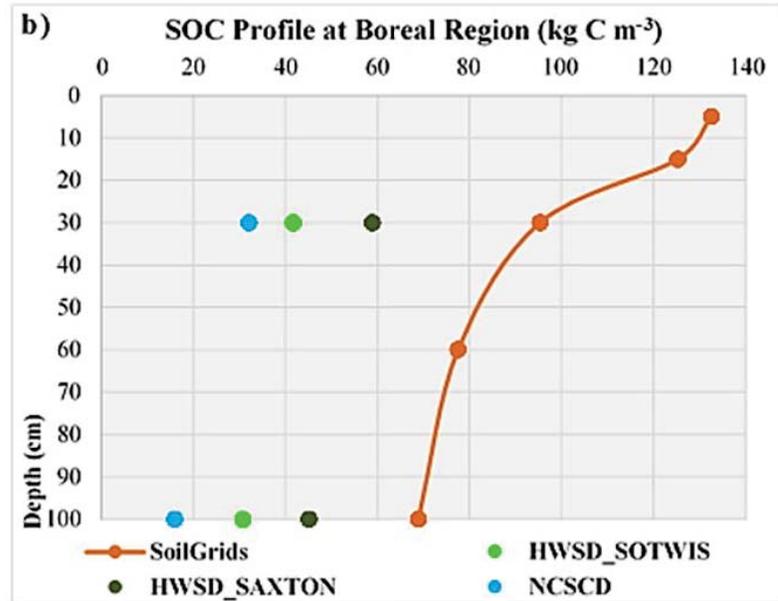
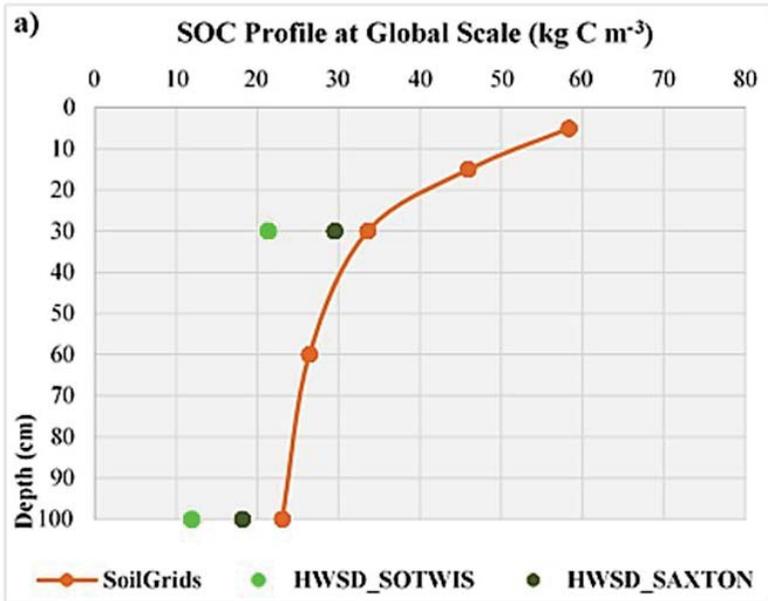


Figure 4.

Difference in Organic Carbon Concentration (kg/100 kg)

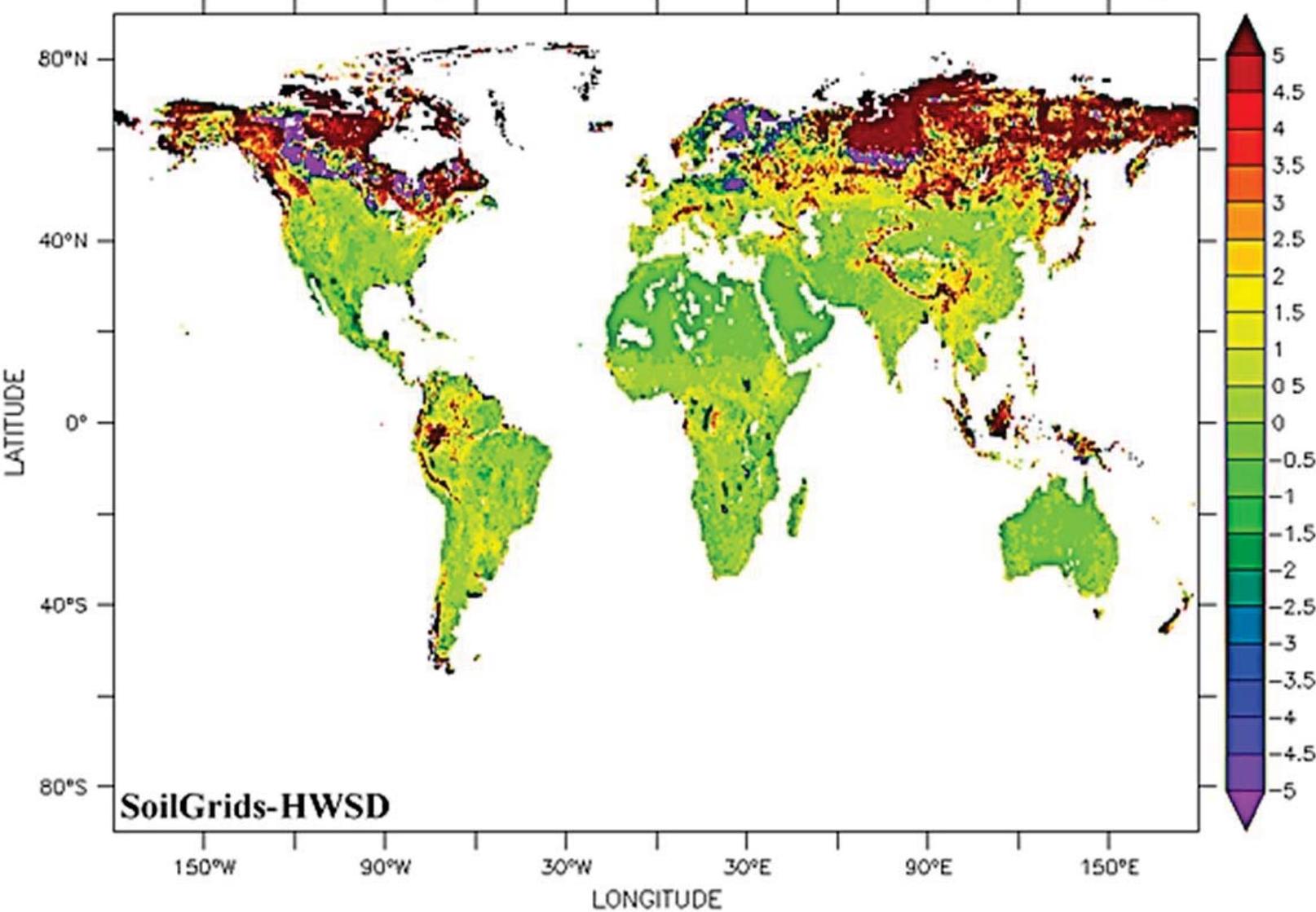


Figure 5.

Difference in Bulk Density (kg m^{-3})

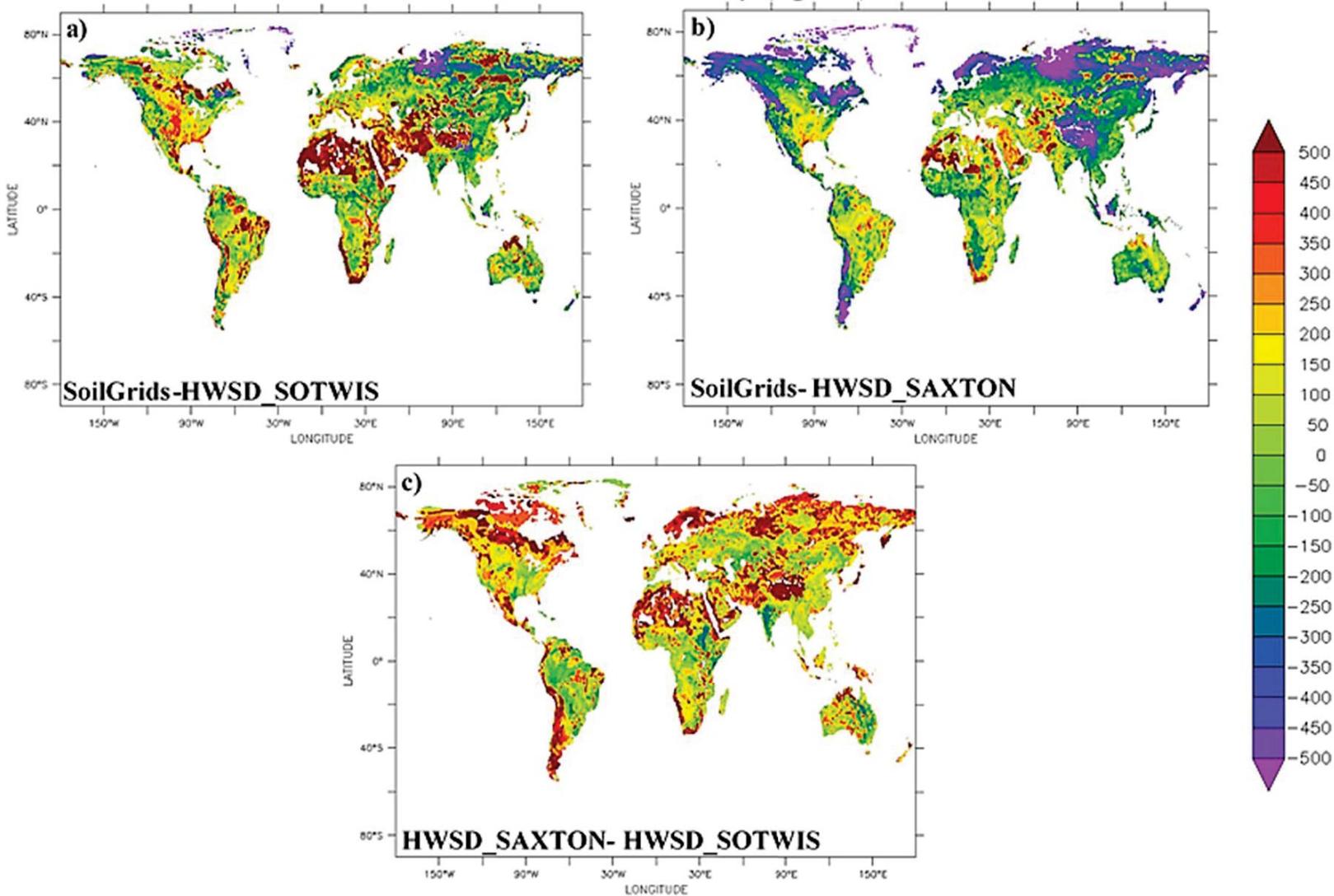
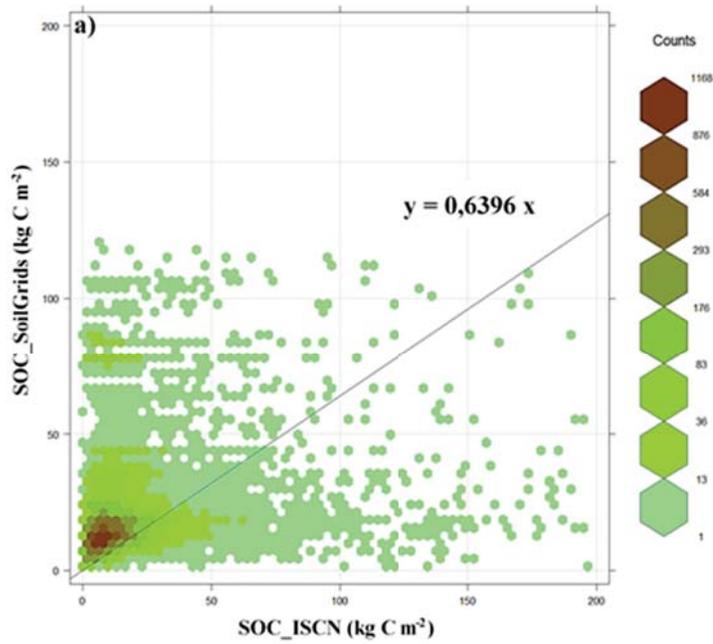
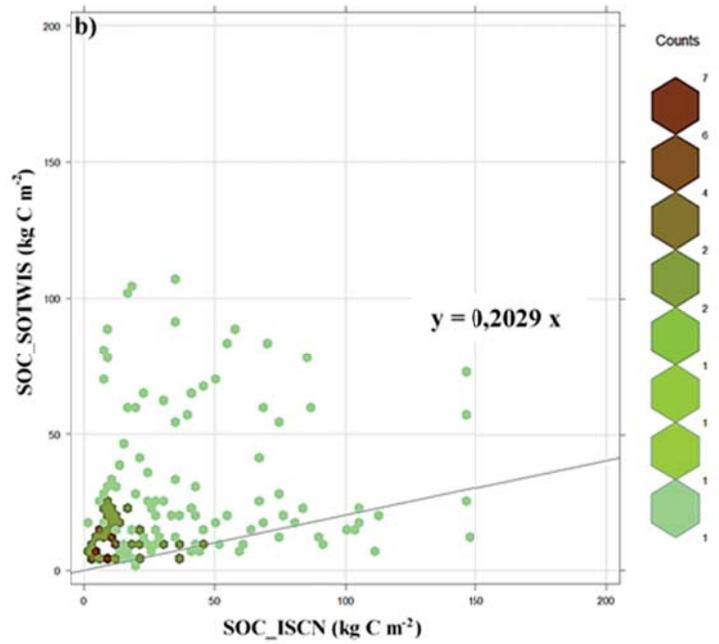


Figure 6.

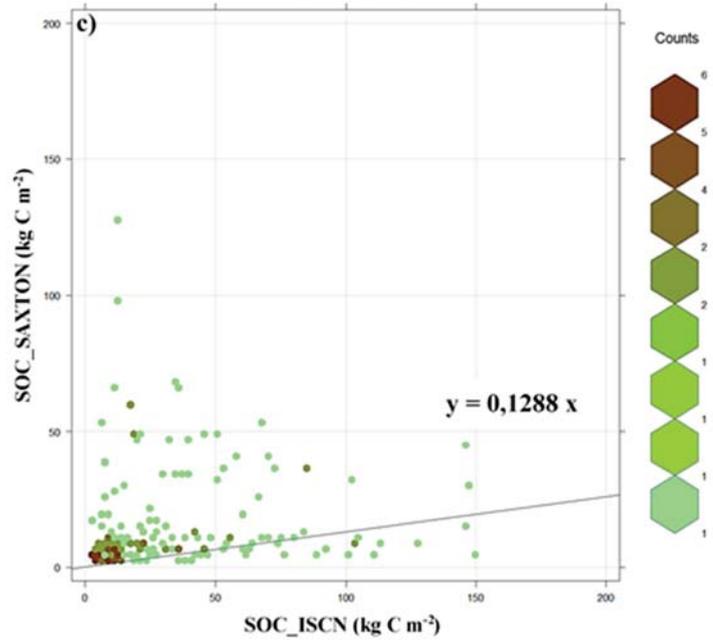
SoilGrids=f(ISCN) (AVE :-0.48)



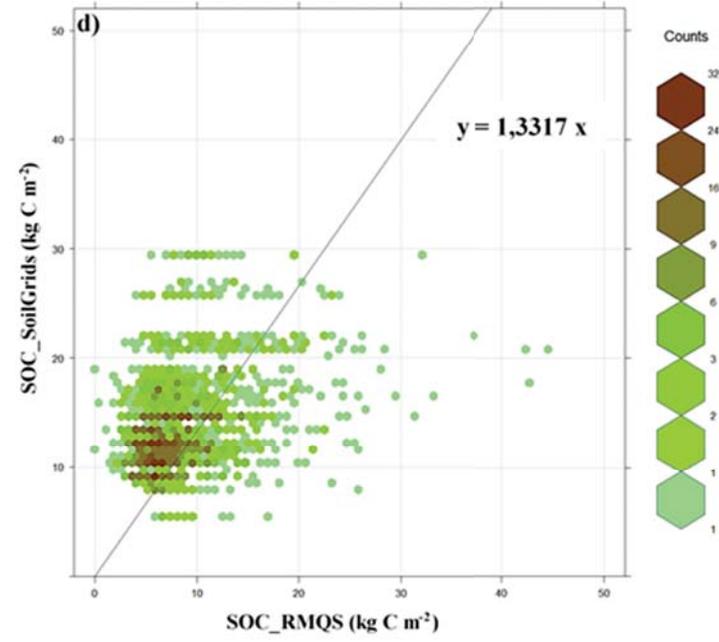
SOTWIS=f(ISCN) (AVE :-0.0088)



SAXTON=f(ISCN) (AVE :-0.19)



SoilGrids=f(RMQS) (AVE :-0.3)



SoilGrids=f(NSI) (AVE :-31)

