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Estimation of soil organic carbon stock and its spatial distribution in the Republic of Ireland

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Abstract

Data scarcity often prevents the estimate of regional (or national) scale soil organic carbon (SOC) stock and its spatial distribution. This study attempts to overcome the data limitations by combining two existing Irish soil databases [SoilC and national soil database (NSD)] at the national scale, to create an improved estimate of the national SOC stock. Representative regression models between the near-surface SOC concentration and those of deeper depths, and between SOC concentration and bulk density (BD) were developed based on the SoilC database. These regression models were then applied to the NSD derived SOC concentration map, resulting in an improved SOC stock and spatial distribution map for the top 10 cm, 30 cm and 50 cm depths. Western Ireland, particularly coastal areas, was found to have higher SOC densities than eastern Ireland, corresponding to the spatial distribution of peatland. We estimated the national SOC stock at 383 ± 38 Tg for the near-surface of 0–10 cm depth; 1016 ± 118 Tg for 0–30 cm depth; and 1474 ± 181 Tg for 0–50 cm depth.

Keywords: National soil database, SoilC database, regression models, national scale

Introduction

Soil is the largest pool of organic carbon in the terrestrial biosphere, and minor changes in soil organic carbon (SOC) storage can impact atmospheric carbon dioxide concentrations (Johnston *et al*., 2004; Xu *et al*., 2011). Estimates of SOC stock are required to assess the role of soil in the global carbon cycle (Yang *et al*., 2007). However, the existing estimates for the Republic of Ireland (Tomlinson, 2005; Eaton *et al*., 2008) generally rely on a limited soil database (Gardiner & Radford, 1980) or directly exploit datasets from the UK (Bradley *et al*., 2005). The National Soil Database (NSD) project was conducted to update soil information at the national scale (Fay *et al*., 2007) where SOC concentration was measured for the near-surface soils (0–10 cm) throughout Ireland. Based on this NSD database, McGrath & Zhang (2003), Zhang & McGrath (2004) and Zhang *et al*. (2008) successfully applied geostatistics and GIS techniques to interpolate the near-surface (0–10 cm) SOC concentrations to map the spatial distribution of SOC concentration for the Republic of Ireland. However, it is still difficult to estimate the SOC stock [the product of SOC concentration, bulk density (BD) and soil depth considered] especially for deeper layers because BD and SOC concentrations were not measured below 10 cm in the NSD study. According to previous studies, the SOC concentration of the near-surface soil is well correlated with that of deeper soil (Jobbágy & Jackson, 2000; Yang *et al*., 2007; Meersmans *et al*., 2009b,c; Vasques *et al*., 2010). Bulk density is well correlated with SOC concentration (Manrique & Jones, 1991; Yang *et al*., 2007). Therefore, we hypothesize that the near-surface SOC concentration can be used to estimate SOC concentrations at deeper layers and that the SOC concentration can be used to estimate BD. We can therefore expand the NSD and NSD derived soil information to estimate the SOC stock not only for the near-surface but also for deeper soils for the Republic of Ireland. The SoilC database (Kiely *et al*., 2010) provides an opportunity to test the above hypothesis, as this database includes both the SOC concentration and BD measurements for major Irish land use and soil types in depth increments.

The aims of this study were: (1) to estimate SOC concentrations at deeper layers using near-surface SOC concentration, (2) to estimate BD using SOC concentration and (3) to expand the NSD information to estimate the

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spatial distribution of the SOC stock for the Republic of Ireland at the near-surface and at depth.

Materials and methods

Databases

For the national soil database (NSD), soils were taken at fixed sites predetermined from a national grid system with each grid resolution of 10 × 10 km (Fay *et al.*, 2007). Two sites were located in each 10 × 10 km grid. One location was the North-East corner and the other was the centre point of the grid. Altogether 1310 sites were determined throughout the whole country. At each of the 1310 sites, a 20 × 20 m grid was created firstly, and then was partitioned into 16 equal 5 × 5 m subgrids. Soil cores were then taken at the four corners of all of the 16 subgrids with a Dutch auger (Eijkelkamp, the Netherlands). These 25 cores were taken to a depth of 10 cm and bulked to form a field composite sample weighing ca. 2–4 kg. Among the 1310 samples, 295 were analysed for organic carbon using the Walkley & Black method (Walkley & Black, 1934). A correction factor of 1.16 was applied to the organic carbon samples (295 samples) to account for the different methodologies employed. Note that a correction factor of 1.33 was frequently used (Meersmans *et al.*, 2009a), but the factor of 1.16 used in NSD was based on a study for Irish soil (Brogan, 1966). For the remainder of soil samples (1015) organic carbon concentration was determined using a Leco CN-2000 dry combustion analyser.

Based on the NSD dataset, Zhang *et al.* (2008) integrated the data using GIS and Geostatistical tools (Diggle & Ribeiro, 2007) to create the SOC concentration map with a pixel resolution of 2000 m for the whole country at the 0-10 cm depth. A Box–Cox transformation was applied to achieve approximate normality of datasets prior to geostatistical analyses. Variogram surfaces were produced to identify the anisotropic feature of variograms, and the variograms were modelled to provide input parameters for trans-Gaussian kriging. The SOC concentration map was created using best linear unbiased estimation (BLUE) with ArcGIS 9.2 (ESRI Inc., USA). To ensure the BLUE feature, trans-Gaussian kriging was applied because of the non-normality feature of the SOC concentration.

For the SoilC database (Kiely *et al.*, 2010) soil samples were collected at 62 sites for SOC and BD analysis at three depths, 0–10 cm, 10–25 cm and 25–50 cm. The 62 sites were selected from the 1310 NSD sites according to the major combinations of land use and soil type of Ireland. The SoilC project first classified the 1310 NSD sites into 15 associations of land cover and soil type, with at least three replicates sampled from each association of land cover and soil type (3 × 15 = 45 sites). The remaining sites (17 sites) were then divided among the most dominant associations of land cover and soil type. At each site, a 20 × 20 m grid was created with the sampling position at the centre. Soil samples for bulk density were taken using the core method at 5 points, the corners and centre of the grid. The grid was then partitioned into four equal 10 × 10 m subgrids. Samples were taken at the corners of all of the four subgrids which amounted to nine samples. The nine samples were then bulked to one composite sample for organic carbon analysis. Organic carbon concentration was determined using a Leco CN-2000 dry combustion analyser.

In this study, the CORINE (Co-ordination of Information on the Environment) land cover map was used (Figure 1, Bossard *et al.*, 2000), and 10 land cover classes were adopted, similar to those of Eaton *et al.* (2008), as described in Table 1.

Calculation procedure

1. Relationships between SOC concentration (log-transformed) in the near-surface layer and at depth were determined by regression analysis. We also created the relationship between SOC concentration (natural

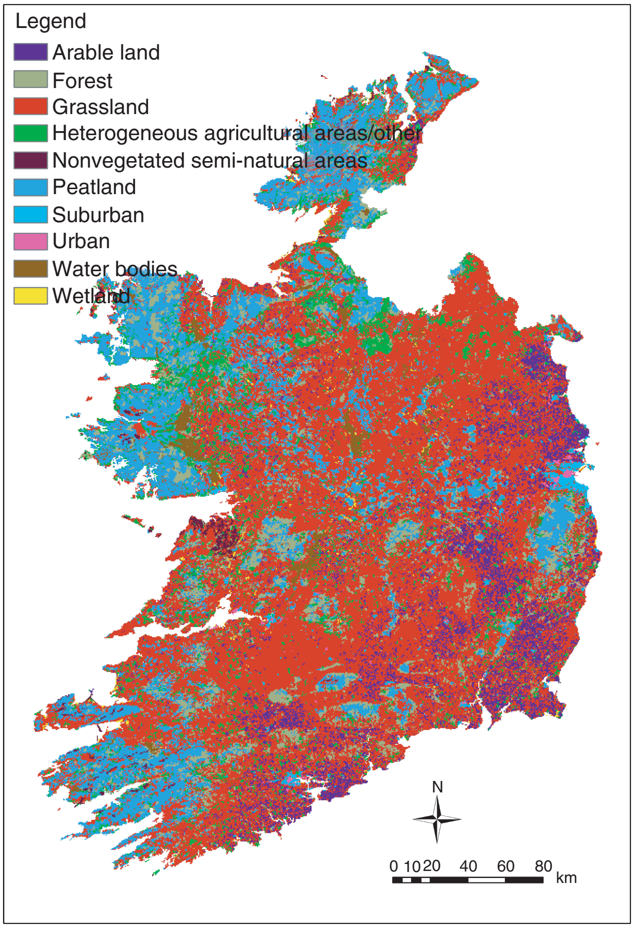

Figure 1 Land cover map CORINE 2000 for the Republic of Ireland (Bossard *et al.*, 2000).

Table 1 Definition for each land cover category (following Bossard *et al*., 2000 and Eaton *et al*., 2008)

Land cover class	Definition
Arable land	All land tilled for crops
Forest	All forest including transitional woodland-shrub
Grassland	Pasture, silage and hay fields, and natural grassland, green urban areas, sport and leisure facilities
Heterogeneous agricultural areas/other	Complex cultivation patterns, land principally occupied by agriculture with significant areas of natural vegetation
Nonvegetated semi-natural areas	Semi natural areas with little vegetation such as beaches, dunes, bare rocks etc.
Peatland	Peat bogs, moors, and heathlands
Suburban	Area of which about half is natural land and half is built-over
Urban	Combination of artificial areas heavily disturbed by humans
Water bodies	All water bodies, not including open ocean and sea
Wetland	All wetland not including those in the peatland class

logarithm-transformed) and BD with the datasets of the three layers (in SoilC) together.

2. The SOC concentrations of the 10–25 cm and 25–50 cm intervals were estimated from the surface (0–10 cm) SOC distribution map (Zhang *et al*., 2008) using the regression relationships from SoilC described above. The BD was estimated from the SOC concentrations using the regression relationship described above. The SOC concentration of the 25–30 cm interval and that of the 30–50 cm interval were calculated as follows:

$$\mathrm{SOC}_{25-30\,\mathrm{cm}} = \frac{\mathrm{SOC}_{10-25\,\mathrm{cm}} + \mathrm{SOC}_{25-50\,\mathrm{cm}}}{2} \quad (1)$$

$$\mathrm{SOC}_{30-50\,\mathrm{cm}} = \mathrm{SOC}_{25-50\,\mathrm{cm}}. \quad (2)$$

The SOC density (SOCD) for each interval was then calculated using the following equation:

$$\mathrm{SOCD}_i = \mathrm{SOC}_i \times \mathrm{BD}_i \times h_i \quad (3)$$

where SOCD_i is the SOC density (t/ha); SOC_i is the soil organic carbon concentration (%); BD_i is the soil bulk density (g/cm^3); and h_i is the soil depth (cm) for the *i*th interval (e.g., 0–10 cm, 10–25 cm, 25–30 cm and 30–50 cm). The SOCD of 0–10 cm, 0–30 cm and 0–50 cm were calculated and analysed in this study.

3. We assumed the SOCD for nonvegetated semi-natural areas, urban and water bodies was 0 (Eaton *et al*., 2008). In the suburban area category, half of suburban area is natural land and half of that is built-over. We therefore reset the SOCD values as half of the estimated values for suburban areas (Eaton *et al*., 2008).

4. The land cover map was overlaid on the SOCD maps to determine the SOCD for each land cover type. Based on the statistics of SOCD for each land cover type, the following formulas were used to calculate SOC stock (SOCS):

$$\mathrm{SOCS}_j = \frac{\mathrm{SOCD}_j \times \mathrm{AREA}_j}{10^{10}} \quad (4)$$

$$\mathrm{SOCS}_i = \sum \mathrm{SOCS}_j \quad (5)$$

where SOCS_j, SOCD_j and AREA_j are the SOC stock (Tg), the SOC density (t/ha) and the area (m^2) for land cover *j* (arable land, forest, grassland and etc.), respectively; SOCS_i is the sum of the SOCS of all land cover types at layer *i* (0–10 cm, 0–30 cm and 0–50 cm). A Monte Carlo simulation was run 10 000 times for the formulas above (equations 4 and 5) based on the statistics of the input (SOCD). The average value and corresponding standard deviation of the 10 000 runs were used as the final estimate and its uncertainty, respectively, for each land cover and each depth.

Statistical methods

Statistical analyses were conducted with SPSS 15.0 (SPSS Inc., USA) and Microsoft Excel 2003 (Microsoft Corporation, USA). Mann–Whitney *U*-tests were conducted with SPSS 15.0 (SPSS Inc) to compare differences in SOC concentration as the data did not satisfy the assumptions of normality. Spatial analysis was conducted with ArcGIS 9.3 (ESRI Inc). Monte Carlo simulation was conducted with SimulAr software (http://www.simularsoft.com.ar/SimulAr1e.htm) added in Microsoft Excel 2003 (Microsoft Corporation, USA).

Results

SOC concentration from NSD and SoilC databases

The SOC concentration of the NSD (0–10 cm) ranges from 1.40 to 55.80%, with a median value of 7.00% (Table 2). Similarly, the near-surface (0–10 cm) SOC concentration of the SoilC database ranges from 1.40 to 52.51%, with a median value of 6.06%. There was no significant difference ($P > 0.05$) between the two databases for 0–10 cm. The SOC concentration decreased with depth in the SoilC database and the lowest layer (25–50 cm) was significantly lower than any of the other two layers (Table 2; $P < 0.05$).

In the SoilC dataset, the near surface (0–10 cm) SOC concentration (log-transformed) can explain more than 90% of the variation of the second layer (10–25 cm) SOC

Table 2 Statistics of soil organic carbon (SOC) concentration (%) for SoilC database and National soil database (NSD)

Database	*N*	Mean	Median	Minimum	Maximum	SD	CV
NSD	1310	13.35	7.00^{A}	1.40	55.80	14.01	1.05
SoilC							
0–10 cm	62	16.30	6.06^{AB}	1.40	52.51	17.60	1.08
10–25 cm	62	13.71	3.87^{B}	0.45	54.80	17.56	1.28
25–50 cm	62	9.75	1.89^{C}	0.25	52.55	16.09	1.65

Different letters (A, B and C) represent statistically significant difference between any two groups (Mann–Whitney *U*-tests) at 0.05 significant levels. SD, standard deviation; CV, coefficient of variation.

concentration (log-transformed) and more than 70% of the variation of the third layer (25–50 cm) SOC concentration (log-transformed) (Figure 2a,b). The SOC concentration (natural logarithm-transformed) can explain 90% of the variation of the BD (Figure 2c).

Distribution of SOCD and SOCS

The SOCD and SOCS values for each land cover type are shown in Table 3. Peatland has the highest SOCD (68 ± 10, 189 ± 33 and 279 ± 58 t/ha for 0–10 cm, 0–30 cm and 0–50 cm, respectively), followed by wetland (62 ± 10, 165 ± 31 and 239 ± 49 t/ha), heterogeneous agricultural areas/other (61 ± 12, 164 ± 37 and 237 ± 59 t/ha), forest (61 ± 12, 163 ± 38 and 236 ± 32 t/ha), grassland (55 ± 11, 145 ± 32, 207 ± 49 t/ha), arable land (47 ± 9, 121 ± 27 and 171 ± 41 t/ha) and suburban areas (25 ± 6, 65 ± 17 and 93 ± 26 t/ha). Grassland has the highest SOCS (Table 3), accounting for about 53% of the total SOCS because of its large area (about 53% of the total land area). Peatland covers about 17% of the total area in Ireland, and accounts for about 21% of the total SOCS. At the national scale, the SOCS of 0–10 cm and of 0–30 cm are 383 ± 38 Tg and 1016 ± 118 Tg (1 Tg = 10^{12} g), respectively, and account for about 26% and 69% of the SOCS of 0–50 cm (1474 ± 181 Tg).

High SOCD can be found in western Ireland where peatlands are widespread and high rainfall predominates (>1200 mm/yr; Figure 3). Southwest Ireland and some parts in the east also present high SOCD. These areas are of high elevation and high rainfall, covered with peatland. In the midlands of Ireland, there are patches of high SOCD areas, corresponding to the distribution of basin peat. In the southeast, low SOCD corresponds to mineral soils with predominantly cropland cover.

Discussion

The SoilC sites (Kiely *et al.*, 2010) were carefully selected from the NSD sites by taking the predominant combinations of land use and soil types of Ireland into consideration.

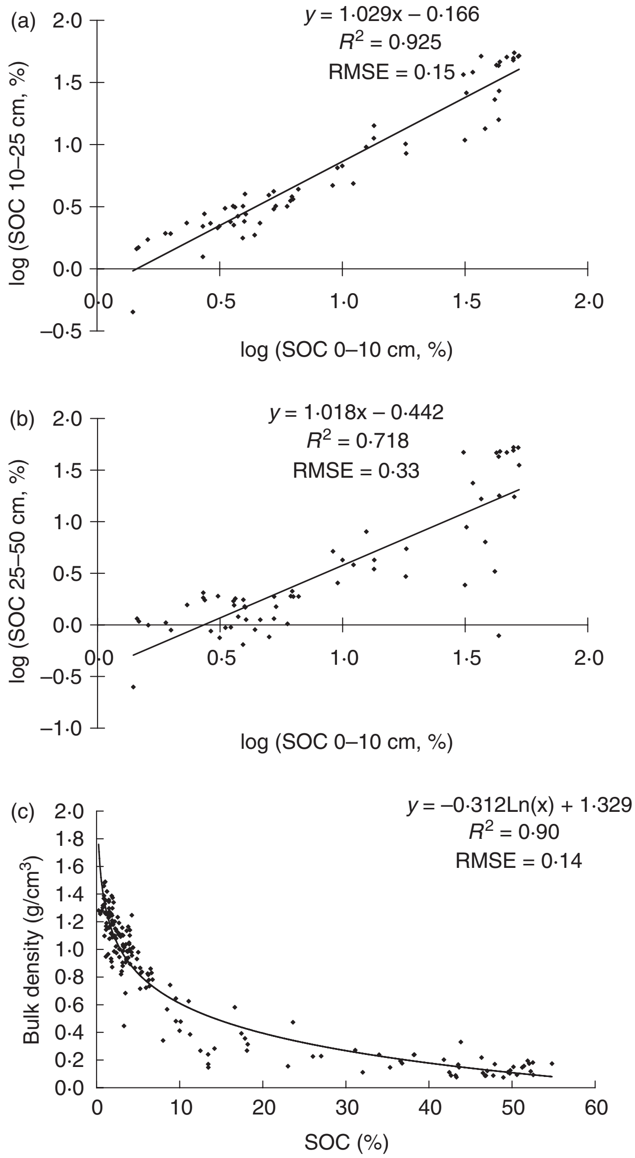

Figure 2 Regression relationships (from the SoilC project) between: (a) log(SOC concentration) at 0–10 cm and that at 10–25 cm depth, (b) log(SOC concentration) at 0–10 cm and that at 25–50 cm depth and (c) soil organic carbon (SOC) concentration and soil bulk density for all the three layers together.

Moreover, the statistical analysis also indicates that the variation of the SoilC near-surface SOC concentration is very similar to that of the NSD, and no statistically significant difference ($P > 0.05$) exists between the two near-surface (0–10 cm) SOC datasets (Table 2). The regression models developed from the SoilC database can therefore be applied to the NSD database and its derivatives (e.g. surface SOC map from Zhang *et al.*, 2008).

The BD and SOC concentrations (%) are the two prerequisites for estimating SOC density (and stocks). However, for the regional scale estimates of SOC stocks, the

Table 3 Soil organic carbon density (SOCD) and soil organic carbon stock (SOCS) by land cover

Land cover	Area (km^2)	Area (%)	SOCD (t/ha) 0–10 cm	SOCD (t/ha) 0–30 cm	SOCD (t/ha) 0–50 cm	SOCS (10^{12}g, Tg) 0–10 cm	SOCS (10^{12}g, Tg) 0–30 cm	SOCS (10^{12}g, Tg) 0–50 cm
Arable land	5268	7.7	47 (9)	121 (27)	171 (41)	25 (5)	63 (13)	91 (20)
Forest	6264	9.1	61 (12)	163 (38)	236 (62)	38 (7)	102 (22)	149 (35)
Grassland	36 520	53.3	55 (11)	145 (32)	207 (49)	203 (35)	534 (88)	769 (163)
Heterogeneous agricultural areas/other	5416	7.9	61 (12)	164 (37)	237 (59)	33 (6)	88 (18)	129 (30)
Peatland	11 916	17.4	68 (10)	189 (33)	279 (58)	80 (10)	219 (35)	321 (60)
Suburban	772	1.1	25 (6)	65 (17)	93 (26)	2 (0.4)	5 (1)	8 (2)
Wetland	312	0.5	62 (10)	165 (31)	239 (49)	2 (0.3)	5 (1)	7 (1)
Nonvegetated semi-natural areas/urban/ water bodies	2048	3.0	0	0	0	0	0	0
Sum	68 516	100				383 (38)	1016 (118)	1474 (181)

The values in parentheses are one standard deviation. SOCD, soil organic carbon density; SOCS, soil organic carbon stock.

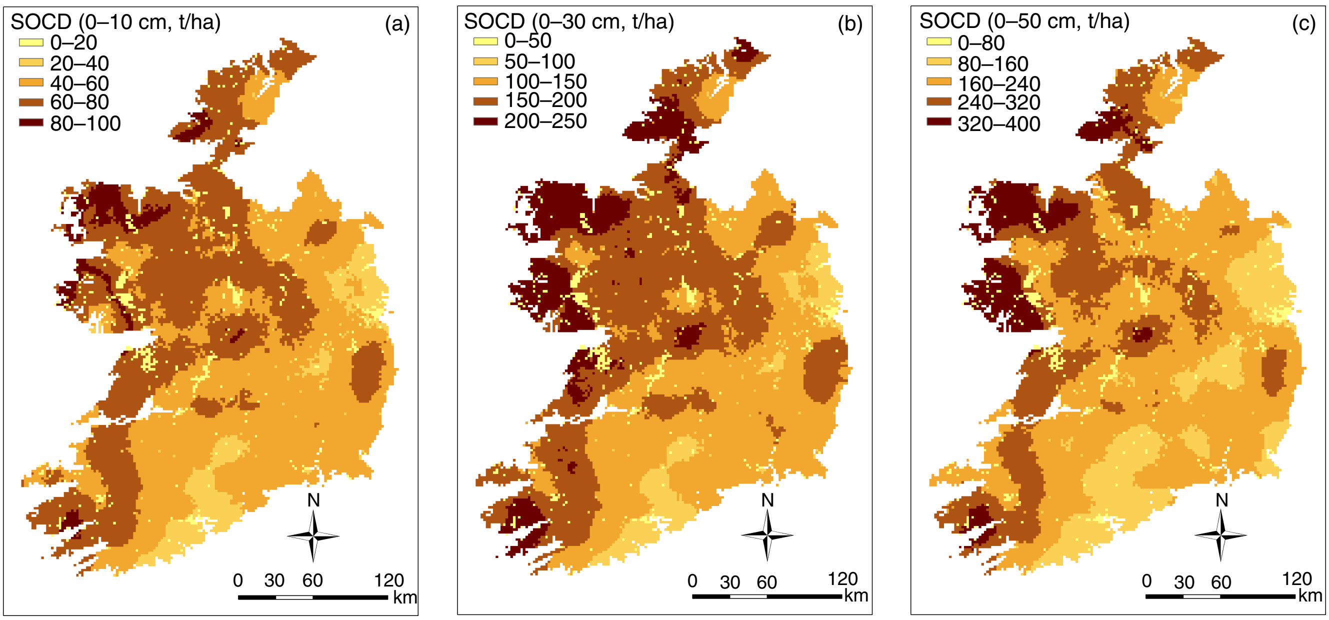

Figure 3 Spatial distribution of soil organic carbon density (SOCD) values for the soils of (a) 0–10 cm, (b) 0–30 cm and (c) 0–50 cm.

spatial representation of both BD and SOC concentrations is often limited. The compilation of the existing datasets and the creation of pedo-transfer functions to estimate BD or SOC concentration from the existing datasets need to be addressed. For BD estimates, Yang *et al.* (2007) developed a negative exponential function with SOC concentration for Chinese soils, and Manrique & Jones (1991) proposed a power function that was widely used for Belgian mineral soils (Meersmans *et al.*, 2008, 2009b,c; van Wesemael *et al.*, 2010). Both of these equations used the SOC concentration as the only input. To estimate BD in this study, a strong negative logarithm function with SOC concentration as the only input was developed (Figure 2c). This function can be used for Irish soils where BD is often absent but SOC concentration is more readily available. Different to Manrique & Jones (1991), our equation is not only suitable for mineral soils but also suitable for organic soils, as the relationship was developed based on data from both mineral and organic soils. For the estimation of SOC concentration at depth, Yang *et al.* (2007) assumed an SOC concentration distribution down the soil profile as a negative exponential function. In this study, linear functions were developed for SOC concentration (logarithm-transformed) between the near-surface and deeper layers (Figure 2a,b). Using these functions (Figure 2a,b), the existing surface SOC map (Zhang *et al*., 2008) was extrapolated to a greater depth for the whole country. However, these regression relationships (Figure 2) are only suitable for top 50 cm depth, and not valid for deeper soils. Further research to examine the vertical change of SOC concentration along the whole soil profile beyond 50 cm depth is required to improve the estimates of soil organic carbon stock at any depth. The data points in Figure 2b showed greater variability at the higher SOC values. It is suggested that a different pedo-transfer function is required for different land use or soil type or their combinations, as was developed by Meersmans *et al*. (2009b,c) for Belgian soils. However, this would require more sites and more detailed data than what is available either in SoilC or in NSD. With updating the two soil databases (NSD and SoilC) and interpolation methods used by Zhang *et al*. (2008), this methodological framework proposed in this study can be used to update the SOCD information at national scale in future.

Our SOCD estimates for grassland (145 ± 32 t/ha) and cropland (121 ± 27 t/ha) are larger than those of Belgian grassland (115 t/ha) and cropland soils (79 t/ha) for the top 30 cm soils (see Meersmans *et al*., 2009b). The high rainfall and poor drainage characteristic of some Irish soils may be the determining factors in this difference. In another study of agricultural regions in Belgium, van Wesemael *et al*. (2010) found that man-made improved drainage conditions on originally poorly drained grassland soils resulted in a decrease in SOC stock. In our estimates, peatland accounts for 21% of the total SOCS, while Eaton *et al*. (2008) and Tomlinson (2005) have estimated 36% and 53%, respectively. The main reason for the difference is that in our study, we use a maximum soil depth of 50 cm, while the other studies use 1 m (Eaton *et al*., 2008) and the entire soil profile (Tomlinson, 2005). As indicated by Eaton *et al*. (2008), the proportion of peatland's SOCS will increase with the increase of the soil depth considered. Overall our estimates (1016 ± 118 Tg for 0–30 cm) are larger than that (728 Tg for 0–30 cm) of Eaton *et al*. (2008). This might suggest that the study using carbon density data from similar land cover types in the UK (Eaton *et al*., 2008) significantly underestimated the soil carbon stock for Ireland. The new estimate (this study) of the total SOCS for 0–30 cm soils in Ireland (1.016 ± 0.118 Pg, Table 3) may account for about 0.14% of the total SOCS of the world soils (684–724 Pg, see Batjes, 1996).

Our estimates of soil organic carbon stock are directly from the latest soil databases of the Republic of Ireland. However, there are still some uncertainty sources in these estimates. For example, our estimates are based on the empirical regression relationships (equations in Figure 2) that can propagate errors into the final estimates. The three layers (0–10 cm, 0–30 cm and 0–50 cm) approach used in this study might also lead to some errors; for example, empirical estimates (equations 1 and 2) were used for the intervals of 25–30 cm and 30–50 cm in this study because no observed data are available. In addition, the surface SOC concentration map (Zhang *et al*., 2008) would also propagate some uncertainties in the final estimates. Although we carried out a Monte Carlo simulation for uncertainty analysis of SOCS estimates, this analysis is still approximate. There remain challenges to quantifying the total uncertainty in our estimates and the contribution of each source to the total uncertainty. Further research is therefore needed.

Conclusions

This study has overcome the lack of data that often prevents estimates of SOC stock and its spatial distribution at the national scale by combing existing interrelated soil databases. Our estimates of SOC stock for the top 10 cm, 30 cm and 50 cm soils of the Republic of Ireland are 383 ± 38 Tg, 1016 ± 118 Tg, 1474 ± 181 Tg, respectively. These estimates are based on the latest indigenous Irish soil databases, along with the spatial distribution information.

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