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An assessment of subsoil organic carbon stocks in England and Wales

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Abstract

It is estimated that half the soil carbon globally is in the subsoil, but data are scarce. We updated estimates of subsoil organic carbon (OC) in England and Wales made by Bradley *et al.* (2005) using soil and land-use databases and compared the results with other published data. We estimated that the soils of England and Wales contained 1633, 1143 and 506 Tg of OC at 0–30, 30–100 and 100–150 cm depths, respectively. Thus, half of the soil OC was found below 30 cm depth. Peat soils accounted for the largest proportion, containing 44% of all the OC below 30 cm despite their small areal extent, followed by brown soils, surface-water gley soils, ground-water gley soils and podzolic soils. Peat soils had more than 25% of their profile OC per unit area in the 100–150 cm depth, whereas most other soils had <8% at this depth. The differences between soil types were consistent with differences in soil formation processes. Differences in depth distributions between land uses were small, but subsoil OC stocks in cultivated soils were generally smaller than in soils under grassland or other land uses. Data on subsoil OC stocks in the literature were scarce, but what there was broadly agreed with the findings of the above database exercise. There was little evidence by which to assess how subsoil OC stocks were changing over time.

Keywords: Soil type, land use, land-use change, databases, literature review, monitoring

Introduction

It is estimated that over half the soil organic carbon (OC) globally is stored in the subsoil below 15–30 cm depth (Batjes, 1996; Jobbágy & Jackson, 2000). However, our knowledge and understanding of soil OC is largely restricted to the topsoil, most research having been done there, because it is more readily accessible and most obviously influenced by the inputs and losses of C as they interact with the environment (King *et al.*, 2005). National soil-monitoring schemes generally assess just the upper 15–30 cm of the profile (Bellamy *et al.*, 2005; Emmett *et al.*, 2010). The effects of soil type, climate, management and other drivers on subsoil OC are largely unknown (Harrison *et al.*, 2011; Poeplau *et al.*, 2011; Rumpel & Kögel-Knabner, 2011; Schmidt *et al.*, 2011). The reasons for this neglect include the time-consuming and arduous task of sampling subsoil, and the traditional view that subsoil OC is stable. However, there is increasing interest in the nature and properties of subsoil OC and its importance in the global C cycle (e.g. Jenkinson *et al.*, 2008; Chabbi *et al.*, 2009; Rumpel & Kögel-Knabner, 2011; Schmidt *et al.*, 2011; Chapman *et al.*, 2013).

In this paper, we estimate stocks of subsoil OC in England and Wales using existing spatial databases on soils and land use, building on the work of Bradley *et al.* (2005). We also review other published information on subsoil OC stocks in England and Wales, focusing on the effects of soil type and land use.

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Methodology

Database exercise

We obtained the spatial distribution of soil types and land uses across England and Wales by overlaying the 1:100 000 Countryside Survey Land Cover Map for 1990 (LCM; Fuller *et al.*, 1993) on the 1:250 000 National Soil Map (NATMAP; Mackney *et al.*, 1983) and finding the area of each soil series–land use combination in 1 km grid squares. We then obtained data on soil properties down the soil profile for each of the soil series–land use combinations from data held in the LandIS database (www.landis.org.uk; Proctor *et al.*, 1998). We followed broadly the same approach as Bradley *et al.* (2005) except we used a different method to combine the data on soil type and land use and we included data to 150 cm depth, whereas Bradley *et al.* used only data to 100 cm. Note that not all soils in England and Wales are 150 cm deep: many are shallower and some are deeper. The details are as follows.

Spatial distribution of soil types and land use. The NATMAP, created by the Soil Survey of England and Wales (SSEW), gives the distribution of 296 soil associations, each comprising between one and eight soil series found together in particular landscapes. We created a soil series dataset at 1 km resolution from the NATMAP by integrating the fraction of each soil association in each 1 km square with the fraction of all the soil series in each soil association. To determine the soil series–land use combinations in each square, we obtained the fraction of each land use in each square using the LCM and then multiplied the coverage of the soil series by the coverage of the land use. This contrasted with the approach of Bradley *et al.* (2005) who combined the soil and land use data according to eight sets of rules (combining either the dominant or each land use type in each square with the dominant or each of up to five soil types, soil type having been defined by combining soil series at the sub-group level) and taking the average result across the eight. We used the three land-use categories specified in the LandIS database: cultivated land (mainly arable but also rotational grassland); permanent managed grassland; and '*other*'. The *other* land-use category covers all land not under cultivation or managed grassland and refers to land under semi-natural or natural vegetation characteristic of England and Wales including salt marsh, bog, fen, rough grassland, lowland heath, heather moorland, the uplands and all woodland.

Soil profile data. We extracted soil OC content, stoniness and bulk density data from the Horizon Fundamentals dataset in LandIS for each soil series–land use combination identified above. The Horizon Fundamentals dataset was created with data from 1289 soil profiles sampled to characterize soil series during detailed field survey by the SSEW (Hallett *et al.*, 1995). For the majority of soil series, multiple datasets are available, and mean parameter values were calculated. The topsoil (0–15 cm) OC data obtained from the profiles were augmented by data from the National Soil Inventory (Bellamy *et al.*, 2005), stratified by soil series and land use. Soil sampling and laboratory analyses followed standard SSEW procedures (Avery & Bascomb, 1982), with soil OC measured by the modified Walkley–Black method (Nelson & Sommers, 1996) on the fine earth fraction (<2 mm). Litter horizons were excluded. The above mapping exercise identified 434 soil series. In cases where the mapping exercise produced a soil series–land use combination for which there was no Horizon Fundamentals data, indicating that this series–land use combination should not occur (this affected 17, 7 and 3% of the soil series under cultivated land, grassland and *other*, respectively), we populated the dataset with data from the most similar land use: for cultivated land, we used grassland data firstly or, if that did not exist, data for *other*; for grassland, firstly with *other* and then cultivated land; and for *other*, firstly with grassland and then cultivated land.

Soil OC stocks. We calculated the soil OC stock per unit area in each depth interval for each soil series–land use combination identified above from:

$$C_i = \hat{C}_i(1 - S_i)\Delta z_i \rho_i \tag{1}$$

where C is the OC stock per unit area (g/m^2), $\hat{C}$ is the OC content per unit mass (g/kg, determined on the <2 mm fraction), S is the stoniness (kg/kg, the >2 mm fraction), Δz is the soil depth increment (m), ρ is the bulk density (kg/m^3), and subscript i indicates the ith depth. We calculated OC stock values for depth intervals 0–30, 30–100 and 100–150 cm by summing the values for individual horizons. Where horizons straddled a boundary between depth intervals, the data were apportioned between the depths *pro rata*. For each of the three depth intervals, we calculated weighted mean OC stocks per unit area for soils classified by their Major Soil Group distinguished by the SSEW (Table 1) under each land use:

$$\bar{C} = \frac{\sum_{j=1}^{n} (w_j C_j)}{\sum_{j=1}^{n} w_j} \tag{2}$$

where $\bar{C}$ is the weighted OC stock per unit area, and C_j and w_j are the OC stock per unit area and its weighting, respectively, for the jth soil series, and:

$$w_j = \frac{A_j}{\sum_{j=1}^{n} A_j} \tag{3}$$

where A_j is the area of the jth series (km^2). The standard deviation of the mean is then:

$$\sigma_i = d\sqrt{\sum_{j=1}^{n} w_j^2} \tag{4}$$

where d is the standard deviation of the set of C_j values, assuming they are equal. The total soil OC stock for each Major Soil Group and land use combination in England and

Table 1 The Major Soil Groups[a] of the SSEW soil classification system (Avery, 1980)

Major Soil Group	Description
Lithomorphic soils	With distinct humose or organic topsoil over C horizon or bedrock at 40 cm or less and no diagnostic B or gleyed horizon within that depth
Pelosols	Slowly permeable (when wet) non-alluvial clayey soils with B or BC horizon showing vertic features and no E, non-calcareous BG or paleo-argillic horizon
Brown soils	Soils excluding pelosols, with weathered, argillic or paleo-argillic B and no diagnostic gleyed horizon at 40 cm or less
Podzolic soils	With podzolic B horizon
Surface-water gley soils	Non-alluvial soils with distinct, humose or peaty topsoil, non-calcareous Eg and/or Bg or Btg horizon and no G or relatively pervious Cg horizon affected by free groundwater
Ground-water gley soils	With distinct humose or peaty topsoil and diagnostic gleyed horizon at less than 40 cm in recent alluvium ripened to more than 20 cm, and/or with G or relatively pervious Cg horizon affected by free ground water
Man-made soils	With thick man-made A horizon or disturbed soil (including material recognisably derived from pedogenic horizons) more than 40 cm thick
Peat soils	Having more than a specified content of OC, depending on the clay content of the mineral fraction

[a]Terrestrial raw soils and Raw gley soils omitted (they account for <1% of the land area).

Wales is then given by multiplying the stock per unit area by the total area occupied by the combination.

Literature review

A literature review on subsoil OC stocks in England and Wales was conducted largely through the web-based ISI Web of Knowledge [SM] search engine (Thomson Reuter, New York, USA). Where given, we reported principal site and soil attributes, and the OC stock by depth. We list the soil type by both the SSEW Major Soil Group (Table 1) and the Reference Soil Group of the UN Food and Agriculture Organization World Reference Base (WRB) system (IUSS-ISRIC-FAO, 2006). We used the same OC stock units, land use and depth categories and methods as mentioned previously, except for uncultivated soils where, if reported, the 0–30 cm depth was split into separate 0–15 and 15–30 cm intervals to reflect the particular horizonation of such soils. Where the deepest depth interval in the literature failed to attain the lower depth of a standard depth interval, our approach was to extrapolate a given OC stock for the remainder of the corresponding depth interval only if the lower depth given was closer to the standard interval lower depth than the upper depth. In other words, extrapolation of a stock down to 100 or 150 cm depth was only done if the literature reported the stock down to at least 65 or 125 cm, respectively.

Where there were data on OC stocks at a particular site over time, we calculated mean annual changes by dividing the change between measurements by the sampling interval. This assumes the change is linear. This is realistic for intervals of a decade or so under established land management (Bellamy *et al*., 2005; Chapman *et al*., 2013). For longer periods, or following changes in land management, this may be erroneous and the results should be treated with caution.

Results and discussion

Subsoil OC stocks per unit area

Figure 1 shows the OC stocks per unit area obtained from the database exercise for individual soil series by land use. The distributions show a good deal of scatter, reflecting differences between soil types and locations. We attempted to fit exponential (*pace* Bernoux *et al*., 1998) and spline (*pace* Malone *et al*., 2011; Odgers *et al*., 2012) curves to the data, but the fits were poor, and there were insufficient data to fit curves for individual soil types. We therefore analysed the data by specified depth intervals (*cf*. Jobbágy & Jackson, 2000; Goidts & van Wesemael, 2007; Saby *et al*., 2008; Wiesmeier *et al*., 2012).

Table 2 shows the weighted-mean values of soil OC per unit area by depth for the different soil types and land uses. The differences between land uses in the proportions at different depths were small; though, there were clear differences in the total stocks, which increased in the order cultivated land to grassland to *other*. These reflect, in part, differences in plant inputs of C and the intensity of soil disturbance due to management. Subsoil C contents may also reflect past land uses as well as the effects of current managements. For example, much of the subsoil OC under cultivated land is likely to be from former grassland. Based on isotopic signatures, subsoil OC is often much older than topsoil OC (Jenkinson *et al*., 2008).

Peat soils had the largest subsoil OC stocks per unit area, followed by gley soils and podzolic soils, and then pelosols. Peat can contain more than 200 times as much OC as the overlying vegetation (Garnett *et al*., 2001). Lithomorphic and man-made soils had the smallest total OC stocks per unit area and more than 90% of this was at 0–30 cm depth. Most soils had 50–60% of their OC at 0–30 cm depth, except peat soils that had only 20%, with about 30% at

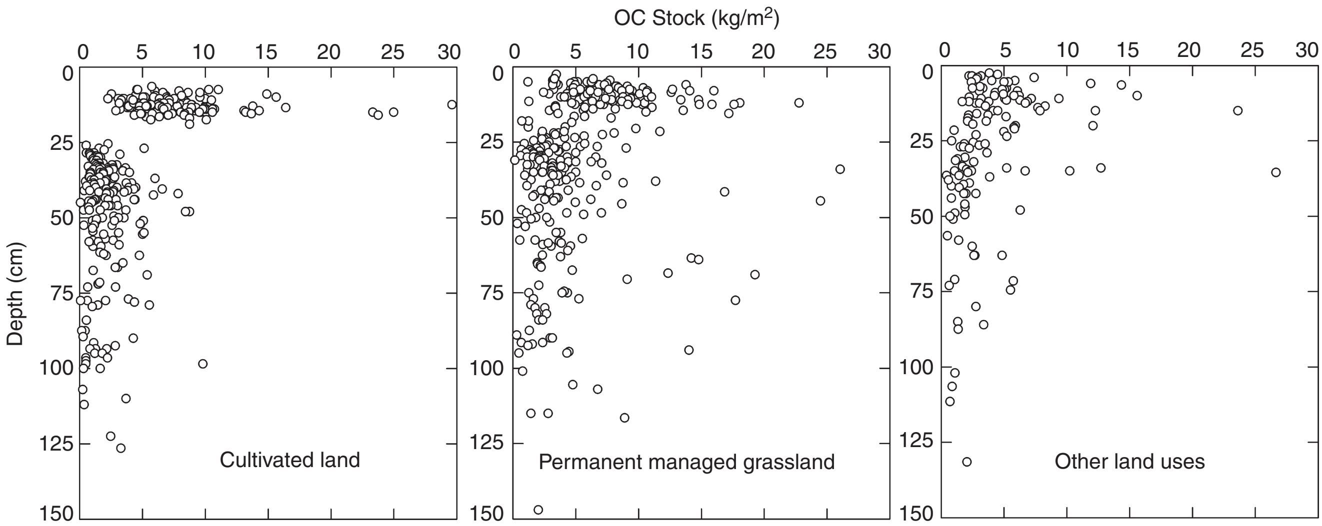

Figure 1 Depth distributions of soil organic C (OC) stocks per unit area from the Horizon Fundamentals dataset in LandIS for the main soil series in England and Wales calculated with equation (1) and grouped by land-use category.

100–150 cm depth. Gley soils and pelosols had 8–17% of their OC at 100–150 cm depth whilst others had <8%. Vanguelova *et al.* (2013) reported similar OC stocks per unit area and depth distributions in a survey of woodland soils across the whole of Great Britain (England, Wales and Scotland).

These results are consistent with the processes of soil formation in different soils. Large subsoil OC stocks in periodically waterlogged gley soils might reflect impaired decomposition of organic matter under anoxic conditions as well as illuviation of dissolved and particulate OC from upper horizons. Illuviation of OC chelated with metals might also account for elevated subsoil OC in podzolic soils. Surface-water gley soils had somewhat larger proportions of their OC in the topsoil than ground-water gley soils, presumably reflecting their different hydrologies. The large stocks at depth in pelosols reflect their vertic properties and resulting seasonal shrinkage and deep cracking which cause topsoil organic matter to be incorporated into depth.

Total subsoil OC stocks

Table 3 shows the total OC stocks for England and Wales subdivided by soil type and land use. Cultivated soils had smaller OC stocks at 30–150 cm depth (393 Tg) than soils under grassland (494 Tg) and *other* land uses (761 Tg). For cultivated land, the order from greatest to smallest stock at 30–150 cm depth was brown soils ≈ peat soils > surface- and ground-water gley soils > pelosols; for grassland, it was brown soils > surface-water gley soils > peat soils > ground-water gley soils > podzolic soils; and for *other* land uses it was peat soils ≫ surface-water gley soils > brown soils > podzolic soils. The overall order across all land uses was peat soils ≫ brown soils ≈ surface-water gley soils > ground-water gley soils > podzolic soils ≈ pelosols.

The results reflected the differences in stock per unit area and the areal extents of the soils. Peat soils were the most important stores of OC in England and Wales overall, containing 44% of all the soil OC present below 30 cm, in spite of their small extent (4% of the total land area). By contrast, brown soils had the greatest areal extent (39% of the total area) but had only small OC contents per unit area. These soils are heavily used for cultivated agriculture in England and Wales.

The estimated total OC stocks in England and Wales for the 0–30 and 30–100 cm depths were 1633 and 1143 Tg, respectively, which compares with 1209 and 870 Tg, respectively, reported by Bradley *et al.* (2005), that is, our estimates were 35 and 31% greater, respectively. The differences were due to the methodological differences outlined earlier. The differences were greater in the *other* land use (79 and 48% more at 0–30 and 30–100 cm depths, respectively) than in cultivated land (16 and 21%, respectively) and grassland (23 and 20%, respectively). A possible explanation is that the most abundant soils have below average OC contents, so that Bradley *et al.*'s method of combining soil and land use data by averaging results obtained with the most abundant soil type in each 1 km square with results obtained for the five most abundant soil types (see Spatial distribution of soil types and land use) leads to under-estimation of stocks. This is more evident in the *other* land use category because the soils are more varied. Interestingly, Vanguelova *et al.* (2013) also estimated the total soil OC stock under woodland in the upper 100 cm in England and Wales to be much greater (69 and 16%, respectively) than the estimates given for woodland soils by

Table 2 Depth distributions of soil organic C (OC) stock per unit area in the upper 150 cm of soils in England and Wales by SSEW Major Soil Group and land use

		OC stock per unit area (kg/m^2)							Fraction of total 0–150 cm stock (%)		
		0–30 cm		30–100 cm		100–150 cm		0–150 cm			
Land use Major Soil Group	Number of soil series *n*	Mean	SD	Mean	SD	Mean	SD	Mean	0–30 cm	30–100 cm	100–150 cm
Cultivated land											
Lithomorphic soils	33	9.97	2.95	0.52	3.36	0.26	3.09	10.75	92.7	4.8	2.5
Pelosols	11	8.46	0.69	5.38	0.71	2.46	0.65	16.30	51.9	33.0	15.1
Brown soils	188	6.67	0.25	3.96	0.29	0.96	0.17	11.59	57.6	34.1	8.3
Podzolic soils	50	11.89	1.73	5.94	0.70	1.22	0.22	19.07	62.4	31.2	6.4
Surface-water gley soils	58	7.63	1.44	4.57	0.62	1.66	0.49	13.86	55.1	33.0	12.0
Ground-water gley soils	64	12.34	1.99	8.19	2.64	4.21	1.77	24.75	49.9	33.1	17.0
Man-made soils	19	5.13	1.96	0.44	0.81	0.10	0.29	5.68	90.4	7.8	1.8
Peat soils	7	36.67	4.09	82.99	5.55	46.29	4.94	165.99	22.1	50.0	27.9
Permanent managed grassland											
Lithomorphic soils	33	11.78	2.39	0.58	3.05	0.11	2.85	12.47	94.5	4.6	0.9
Pelosols	11	10.49	1.11	6.76	1.06	2.26	0.59	19.51	53.8	34.6	11.6
Brown soils	188	9.29	0.42	4.73	0.34	0.86	0.19	14.88	62.4	31.8	5.8
Podzolic soils	50	13.22	2.53	6.17	1.10	1.00	0.36	20.39	64.8	30.2	4.9
Surface-water gley soils	58	10.80	1.30	5.77	0.65	1.80	0.48	18.37	58.8	31.4	9.8
Ground-water gley soils	64	11.93	2.21	7.99	2.45	3.89	1.66	23.82	50.1	33.6	16.3
Man-made soils	19	5.98	2.95	0.12	1.02	0.01	0.36	6.11	97.8	2.0	0.2
Peat soils	7	31.77	4.75	76.63	3.08	50.88	3.17	159.22	19.9	48.1	31.9
Other land uses											
Lithomorphic soils	33	13.90	1.99	0.47	2.49	0.11	2.33	14.48	96.0	3.2	0.8
Pelosols	11	9.67	0.97	5.92	0.54	2.18	0.51	17.77	54.4	33.3	12.3
Brown soils	188	9.08	0.47	4.31	0.34	0.79	0.19	14.18	64.0	30.4	5.6
Podzolic soils	50	18.55	2.12	5.33	0.70	0.80	0.24	24.67	75.2	21.6	3.2
Surface-water gley soils	58	15.46	2.04	8.11	0.90	2.17	0.57	25.74	60.1	31.5	8.4
Ground-water gley soils	64	14.38	2.38	6.42	2.37	2.61	1.65	23.41	61.4	27.4	11.2
Man-made soils	19	4.88	2.56	0.04	0.88	0.00	0.32	4.92	99.1	0.8	0.0
Peat soils	7	30.75	9.70	79.53	7.14	58.08	5.07	168.38	18.3	47.2	34.5

SD, standard deviation.

Bradley *et al.* (2005). They attributed the differences to uncertainties in land use and soil-type coverage when scaling up, and also highlighted the greater variation associated with non-mineral soils (particularly peat soils) which are likely to be more prominent in the *other* land-use category.

Vanguelova *et al.* (2013) estimated there to be a total of 235 Tg of OC in the top 100 cm of the soils under woodland in England and Wales, and we have estimated here that there was 1044 Tg of OC in the top 100 cm of the soils under all *other* land uses (including woodland). If both these figures are credible, then this would suggest that between 20 and 25% of all soil OC in the top 100 cm of soils under *other* land uses is found specifically in woodland soils.

Despite the differences discussed earlier, we agree with Bradley *et al.* (2005) that around 40% of soil OC in the top 100 cm of the profile was at depths greater than 30 cm. We estimated there to be a further 506 Tg of OC at 100–150 cm depths (15% of the 0–150 cm stock). This gives an improved total OC stock estimate of 3282 Tg in the upper 150 cm of the soils in England and Wales, of which half (1649 Tg) was below 30 cm.

Subsoil OC stocks per unit area from the literature

We found very little data on subsoil OC stocks in England and Wales in the literature review, and not all soil types were covered. With the exception of Bradley *et al.* (2005) and Vanguelova *et al.* (2013), we found only eight studies giving depth distributions of OC with <50 soil profiles described (the database exercise above included more than 1300 profiles). We found several other sources of gravimetric subsoil OC data in England and Wales, but with no bulk density measurements from which to calculate stocks. The full dataset is given in the Supporting Information (Table S1), and a summary is given in Table 4. We have not included the OC data for woodland soils in the study by

Table 3 Depth distributions of total soil organic C (OC) stocks in the upper 150 cm of soils in England and Wales by SSEW Major Soil Group and land use. Note the totals include the small contributions (<0.2%) of the Terrestrial raw soils and Raw gley soils Major Soil Groups

		Total OC stock (Tg)		
Land use Major Soil Group	Area (km^2)	0–30 cm	30–100 cm	100–150 cm
Cultivated land				
Lithomorphic soils	3769	38	2	1
Pelosols	5332	45	29	13
Brown soils	19 929	133	79	19
Podzolic soils	797	9	5	1
Surface-water gley soils	11 559	88	53	19
Ground-water gley soils	6171	77	51	26
Man-made soils	163	1	0	0
Peat soils	741	27	62	34
Total for land use	48 461	419	279	114
Permanent managed grassland				
Lithomorphic soils	3810	45	2	0
Pelosols	2607	27	18	6
Brown soils	26 670	248	127	23
Podzolic soils	4876	65	30	5
Surface-water gley soils	18 077	195	104	33
Ground-water gley soils	4664	56	37	18
Man-made soils	238	1	0	0
Peat soils	719	23	55	37
Total for land use	61 661	660	373	121
Other land uses				
Lithomorphic soils	2232	33	1	0
Pelosols	681	7	4	1
Brown soils	10 322	94	45	8
Podzolic soils	6098	114	33	5
Surface-water gley soils	9850	152	80	21
Ground-water gley soils	2206	31	14	6
Man-made soils	197	1	0	0
Peat soils	3936	121	313	229
Total for land use	35 522	554	490	271
Total for England and Wales	145 644	1633	1143	506

Vanguelova *et al*. (2013) in Table 4 as, strictly speaking, those data were single mean soil OC stock per unit area values for the whole of Great Britain (England, Wales and Scotland) and hence were dependent on measured soil OC stocks for soils in Scotland (where 40% of the sites in their study were located). Nevertheless, we have summarized their data in Table S1, and we discuss their important findings below.

In general, OC stocks reported in the literature were comparable with those in the database exercise, with 20 of the depth horizons reported in Table 4 having a stock within three standard deviations of the mean stock reported in Table 2 for the corresponding soil type and land use (more than 60% of the woodland soil depth horizons summarized by Vanguelova *et al*. (2013) were also within this range). Stocks tended to increase from cultivated land to grassland to *other* land uses, particularly within the same soil type (Ellis & Atherton, 2003; Jenkinson *et al*., 2008). The same pattern was also recently reported for soils in Scotland (Chapman *et al*., 2013). Inevitably, there were some local differences due to site-specific effects. Greater than average OC stocks were recorded for N-fertilized grassland soils at Palace Leas (Hopkins *et al*., 2009), soils converted from cultivated to coarse grass and woodland at Rothamsted (Poulton *et al*., 2003), alluvial soil under cultivation at Shelford (Tye, 2010), and some reclaimed estuarine soils at Sunk Island (Ellis & Atherton, 2003).

Some studies report the effects of management within the same land use. Hopkins *et al*. (2009) found considerably more OC at 0–15 cm but less at 15–30 cm depth under N-fertilized grassland than grassland not receiving N fertilizer at Palace Leas. This may reflect increased plant growth and, hence, increased inputs with N addition. Wilson *et al*. (1997) found that OC stocks at 15–30 cm depth under ancient woodland were greater in brown soil at two sites compared with more recent plantations but that the opposite was true in a podzolic soil at a third site. Vanguelova *et al*. (2013) report greater total soil OC stocks under broadleaved woodland than coniferous woodland in England but the opposite in Wales, although this may simply reflect the geographical distribution of the two woodland types. At Rothamsted, there was more OC under regenerating woodland on a neutral-pH site (Broadbalk 'Wilderness') than an acidic site (Geescroft 'Wilderness') due to differences in previous arable management (Poulton *et al*., 2003).

Evidence for changes in subsoil OC stocks per unit area from the literature

Changes in soil OC with depth over time found in the literature are summarized in Table 5 and given in full in the Supporting Information (Table S2). To the best of our knowledge, there are currently only two sites in England and Wales with published data on subsoil OC at different points in time: Rothamsted in Hertfordshire (Poulton *et al*., 2003; Jenkinson *et al*., 2008) and Palace Leas in Northumberland (Hopkins *et al*., 2009). The UK Environmental Change Network (ECN) monitoring programme includes eight well-characterized terrestrial sites in England and Wales under a range of land uses where, among others, OC is measured on both a 5- (to 30 cm depth) and 20-yr (to 120 cm depth) sampling cycle from 1993 (ECN, 2013). These data are not available currently.

At Park Grass, since 1906 soil under long-term grassland has accumulated OC at a mean annual rate of over 15 g/m^2 in the 30–100 cm layer, although this was off-set by an annual loss of 1 g/m^2 in the upper 15 cm (Jenkinson *et al*., 2008) (assuming a linear change over time – see

Table 4 Evidence from the literature of the soil organic C (OC) stock in the upper 150 cm of soils in England and Wales by SSEW Major Soil Group (Avery, 1980) (and WRB Reference Soil Group, IUSS-ISRIC-FAO, 2006) and land use. Texture is given as the sand (Sa), silt (Si), and clay (C) content where presented or as the texture class [Sa – sand(y), Si – silt(y), C – clay, L – loam(y)]

Land use Major Soil Group [WRB Reference Soil Group]	Location	Parent material	Depth (cm)	Texture [Sa:Si:C (%) or texture class]	pH	OC stock (kg/m^2)	Notes	Reference
Cultivated land								
Pelosol [Luvisol]	Shelford, Notts	Triassic mudstone	0–30	30:35:35[a]	?	3.40	Soil under mixed arable use	Tye (2010)
			30–100	14:42:44[a]		1.75		
Brown soil [Luvisol]	Broadbalk, Rothamsted, Herts	Cretaceous chalk-with-flints	0–30	11:57:32[b]	7.3	3.94	Long-term wheat with N-fertiliser	Poulton *et al.* (2003)
			30–100	16:29:55[b]	7.4	4.75		
Brown soil [Cambisol]	Sunk Island, E. Yorks	Alluvium over Quaternary glacial and lacustrine sediment	0–30	2:56:42	7.7	10.16	Mean of two soils reclaimed from estuary	Ellis & Atherton (2003)
			30–100	6:62:32	7.6	8.41		
			100–150	23:59:18	7.6	4.55		
Brown soil [Cambisol/ Luvisol]	Shelford, Notts	Recent head and alluvial sand over Triassic sandstone	0–30	40:32:28[a]	?	7.12	Mean of five soils under mixed arable	Tye (2010)
			30–100	51:23:27[a]		6.06		
Surface-water gley soil [Luvisol]	Shelford, Notts	Triassic mudstone	0–30	65:20:15[a]	?	3.19	Soil under mixed arable use	Tye (2010)
			30–100	33:31:36[a]		1.62		
Ground-water gley soil [Fluvisol]	Sunk Island, E. Yorks	Alluvium over Quaternary glacial and lacustrine sediment	0–30	3:60:37	7.5	6.49	Mean of two soils reclaimed from estuary	Ellis & Atherton (2003)
			30–100	10:63:27	7.6	10.33		
			100–150	21:61:18	7.6	4.57		
Ground-water gley soil [Fluvisol/ Gleysol]	Shelford, Notts	Alluvial gravel, sand and clay over Triassic mudstone	0–30	51:20:29[a]	?	8.42	Mean of four soils under mixed arable	Tye (2010)
			30–100	84: 6:10[a]		2.06		
Various	Several locations, England and Wales	NA	0–30	NA	NA	7.00	All cultivated soils	Bradley *et al.* (2005)
			30–100			4.00–5.00		
Permanent grassland								
Brown soil [Luvisol]	Park Grass, Rothamsted, Herts	Cretaceous chalk-with-flints	0–15	19:58:23[b]	5.9	5.20	Mean of three long- term treatments	Jenkinson *et al.* (2008)
			15–30	19:58:23[b]	5.9	3.55		
			30–100	13:53:34[b]	5.9	5.13		
Brown soil [Luvisol]	Broadbalk Wilderness, Rothamsted, Herts	Cretaceous chalk-with-flints	0–15	18:55:27[b]	7.4	4.68	Grazed grass from natural regeneration	Poulton *et al.* (2003)
			15–30	15:50:35[b]	7.6	3.19		
			30–100	14:30:56[b]	7.5	5.18		
Brown soil [Cambisol]	Sunk Island, E. Yorks	Alluvium over Quaternary glacial and lacustrine sediment	0–15	1:52:47	7.4	4.66	Soil reclaimed from estuary	Ellis & Atherton (2003)
			15–30	1:51:48	7.4	4.61		
			30–100	2:65:33	7.6	11.47		
Surface-water gley soil [Luvisol]	Palace Leas, Cockle Park, Northumb	Carboniferous shale	0–15	46:27:27[c]	5.6	6.25	Mean of four treatments, no N	Hopkins *et al.* (2009)
			15–30	40:27:33[c]	?	3.43		

Table 4 (continued)

Land use Major Soil Group [WRB Reference Soil Group]	Location	Parent material	Depth (cm)	Texture [Sa:Si:C (%) or texture class]	pH	OC stock (kg/m^2)	Notes	Reference
Surface-water gley soil [Luvisol]	Palace Leas, Cockle Park, Northumb	Carboniferous shale	0–15	48:25:27[c]	4.1	12.72	Mean of two treatments with N	Hopkins *et al.* (2009)
			15–30	46:26:28[c]	?	2.87		
Various	Several locations, England and Wales	NA	0–30	NA	NA	8.00–9.00	All permanent grassland soils	Bradley *et al.* (2005)
			30–100			5.00		
Other land uses								
Brown soil [Luvisol]	Broadbalk Wilderness, Rothamsted, Herts	Cretaceous chalk-with-flints	0–15	18:55:27[b]	7.4	5.35	Coarse grasses from natural regeneration	Poulton *et al.* (2003)
			15–30	15:50:35[b]	7.5	3.68		
			30–100	14:30:56[b]	7.5	5.87		
Brown soil [Luvisol]	Broadbalk Wilderness, Rothamsted, Herts	Cretaceous chalk-with-flints	0–15	20:52:28[b]	7.7	5.09	Regenerated mixed deciduous wood	Poulton *et al.* (2003)
			15–30	19:54:27[b]	7.8	3.49		
			30–100	14:33:53[b]	7.7	6.05		
Brown soil [Luvisol]	Geescroft Wilderness, Rothamsted,Herts	Cretaceous chalk-with-flints	0–15	23:54:23[d]	4.5	4.12	Mean of two soils under regenerated oak and ash wood	Poulton *et al.* (2003)
			15–30	20:47:33[d]	4.7	2.91		
			30–100	17:29:54[d]	5.7	5.07		
Brown soil [Cambisol]	Frilsham and Binfield, Berks	Tertiary London Clay (with or without loess)	0–15	SiCL/SL	3.8	6.30	Mean of two soils under ancient oak wood	Wilson *et al.* (1997)
			15–30	CL/SL	3.9	3.40		
Brown soil [Cambisol]	Yattendon and Binfield, Berks	Tertiary London Clay (with or without loess)	0–15	SiCL/SL/CL	3.9	4.90	Mean of two soils under oak plantation	Wilson *et al.* (1997)
			15–30	SL/CL	4.1	2.30		
Podzolic soil [Cambisol]	Bolderwood, Hants	Tertiary Barton Sand	0–15	SaSiL	3.9	4.90	Ancient oak and beech wood	Wilson *et al.* (1997)
			15–30	LS	4.0	2.40		
Podzolic soil [Cambisol]	Bolderwood, Hants	Tertiary Barton Sand	0–15	SL	3.9	6.90	Oak and beech plantation	Wilson *et al.* (1997)
			15–30	LS	3.9	2.50		
Peat soil [Histosol]	Moor House, Cumbria	Limestone bedrock and glacial till	0–30	?	?	4.70–17.60	Data from soils under moorland	Garnett *et al.* (2001)
			30–100			2.10–31.90		
Peat soil [Histosol]	Broomhead Moor, S. Yorks	Carboniferous Millstone Grit	0–30	?	?	11.00–28.70	Data from soils under moorland	Rawlins *et al.* (2009)
			30–100			25.60–66.90		
			100–150			18.30–47.80		
Various	Several locations, England and Wales	NA	0–30	NA	NA	11.00–12.00	All semi-natural (vegetated) soils	Bradley *et al.* (2005)
			30–100			12.00–17.00		
Various	Several locations, England and Wales	NA	0–30	NA	NA	10.00–12.00	All woodland soils	Bradley *et al.* (2005)
			30–100			7.00–8.00		

[a]texture data read manually from a graph; [b]texture data from Avery & Catt (1995); [c]texture data from Shiel (1986); [d]texture data from Jenkinson (1971); NA, not applicable (average data); ?, not given.

Table 5 Evidence from the literature on changes in soil organic C (OC) stocks over time in the upper 100 cm of soils in England and Wales by SSEW Soil Group (Avery, 1980) under continuous land use or land use change. Refer to Table 4 for further site and soil details

Continuous land use or land-use change Major Soil Group	Location	Years of monitoring	Depth (cm)	Change in OC stock ($g/m^2/yr$)	Notes	Reference
Continuous: Cultivated land						
Brown soil	Broadbalk, Rothamsted, Herts	1893–1904	0–30	+23.3	Long-term wheat with N-fertiliser	Poulton *et al.* (2003)
			30–100	+7.1		
		1904–1999	0–30	+2.7		
			30–100	+5.8		
Continuous: Permanent managed grassland						
Brown soil	Park Grass, Rothamsted, Herts	1870–1876	0–15	−86.9	Mean of two long-term treatments	Jenkinson *et al.* (2008)
			15–30	−64.1		
			30–100	−75.6		
		1876–1906	0–15	+0.3		
			15–30	−0.3		
			30–100	+0.8		
		1906–1999	0–15	−1.0		
			15–30	+1.1		
			30–100	+15.4		
Surface-water gley soil	Palace Leas, Cockle Park, Northumb	1982–2006	0–15	+5.3	Mean of four treatments, no N	Hopkins *et al.* (2009)
			15–30	+7.8		
Surface-water gley soil	Palace Leas, Cockle Park, Northumb	1982–2006	0–15	+85.1	Mean of two treatments with N	Hopkins *et al.* (2009)
			15–30	−12.1		
Change: Cultivated land to Permanent managed grassland						
Brown soil	Broadbalk Wilderness, Rothamsted, Herts	1881–1999	0–15	+25.0	Wheat to grazed grassland	Poulton *et al.* (2003)
			15–30	+14.6		
			30–100	+10.4		
Change: Cultivated land to Other land uses						
Brown soil	Broadbalk Wilderness, Rothamsted, Herts	1881–1964	0–15	+33.7	Wheat to coarse grasses	Poulton *et al.* (2003)
			15–30	+19.6		
			30–100	+11.7		
		1964–1999	0–15	+23.9		
			15–30	+16.9		
			30–100	+14.9		

Table 5 (continued)

Continuous land use or land-use change Major Soil Group	Location	Years of monitoring	Depth (cm)	Change in OC stock ($g/m^2/yr$)	Notes	Reference
Brown soil	Broadbalk Wilderness, Rothamsted, Herts	1881–1904	0–15	+32.3	Wheat to mixed deciduous wodland	Poulton *et al.* (2003)
			15–30	+19.9		
			30–100	+25.5		
		1904–1964	0–15	+31.8		
			15–30	+18.9		
			30–100	+15.8		
		1964–1999	0–15	+20.5		
			15–30	+12.5		
			30–100	+5.7		
Brown soil	Geescroft Wilderness, Rothamsted, Herts	1883–1904/65	0–15	+19.0	Mean of two soils from wheat to oak and ash woodland	Poulton *et al.* (2003)
			15–30	+11.2		
			30–100	+ 4.3		
		1904/65–1999	0–15	+23.6		
			15–30	+14.2		
			30–100	+33.2		

Methodology). Perhaps more surprising was that soils under long-term cultivation at Broadbalk accumulated OC at nearly 6 g/m^2 annually over the same period in the same layer (Poulton *et al.*, 2003). This represents a considerable increase and might be partly explained by improved crop yields from advances in plant breeding and crop management over the past century, which will have increased the amount of OC returned to the soil. Palace Leas provides evidence of more recent changes (1982–2006). Average annual accumulations of OC were up to 8 g/m^2 in the upper 30 cm in soils not receiving N fertilizer. Only in soils receiving N fertilizer was there a mean annual loss of OC (-12 g/m^2) in the 15–30 cm depth, but this was offset by a large accumulation in the depth above. Hopkins *et al*. (2009) reported that any OC decreases were of the same order of magnitude as changes in bulk density (from which stocks are derived), itself dependent on the water content at the time of sampling in non-rigid soils, and that overall there were few significant changes in OC with time. Accumulation of OC at Palace Leas was far greater than at Park Grass, which may reflect the different soil and climatic conditions, Palace Leas being cooler and on a gley soil, whereas Park Grass is on a brown soil under warmer conditions.

There have been large increases in soil OC at the 'Wilderness' (naturally regenerated woodland) experiments at Broadbalk and Geescroft as the land was taken out of cultivation in the 1880s. Annual accumulation rates were initially greater for Broadbalk from the 1880s, but since the 1960s rates have been much greater for Geescroft (47 g/m^2) than Broadbalk (18 g/m^2) in the 15–100 cm layers (Poulton *et al*., 2003). The soil pH at Geescroft has fallen to 4.4, and there are few ground-cover plant species as a result, compared with Broadbalk which has retained its neutral pH through previous liming (Poulton *et al*., 2003). Increased acidity at Geescroft may have caused a slowing of organic matter decomposition and a consequent increase in the OC accumulation rate. More OC accumulated in the subsoil under managed and coarse grassland than under woodland at Broadbalk (Poulton *et al*., 2003). It is likely that soils take a considerable time to equilibrate to a change in land use (Poulton *et al*., 2003; Schipper *et al*., 2007; Smith *et al*., 2007). Subtle changes within land uses may also affect OC contents down the profile, such as different crop rooting patterns (Helfrich *et al*., 2007), use of fertilizers to increase the productivity (Richards & Webster, 1999; Hopkins *et al*., 2009), and use of different tillage practices (Vinten *et al*., 2002; Sun *et al*., 2011; Chapman *et al*., 2013).

A full evaluation of the current dynamics of subsoil OC in England and Wales is not possible due to the lack of evidence. A comparison of the results here with measured changes in topsoil OC across England and Wales (Bellamy *et al*., 2005; Kirk *et al*., 2013) is therefore premature. However, from our limited data, there is no evidence of a significant change in OC stocks below 30 cm under long-term arable or grassland currently (Poulton *et al*., 2003; Jenkinson *et al*., 2008; Hopkins *et al*., 2009). Chapman *et al*. (2013) have recently reported much the same for C stocks in the upper 100 cm in the soils in Scotland over the period 1978–2009. Future assessments of the status and dynamics of subsoil OC stocks will benefit from a more systematic monitoring programme at benchmark sites (e.g. ECN, 2013) and advances in modelling (e.g. Jenkinson & Coleman, 2008).

Conclusions

We estimate that the soils of England and Wales contain 3282 Tg of OC in the upper 150 cm and that half of this (1649 Tg) is found below 30 cm. Subsoil OC stocks vary with soil type and land use. Peat soils and other periodically wet soils had the largest OC stocks at depth. There was a general increase in soil OC stocks from cultivated land to grassland to *other* land uses reflecting, in part, differences in plant inputs and intensity of soil disturbance through management. Subsoil OC stocks probably equilibrate slowly over time when a change occurs, such as land use change. There is very little evidence with which to assess whether subsoil OC stocks in England and Wales are changing. What evidence we do have suggests that subsoil OC stocks under long-term management are stable.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Evidence from the literature of the soil organic C content and stock in the upper 200 cm of soils in England and Wales by soil type and land use.

Table S2. Evidence from the literature of the change in soil organic C content and stock in the upper 100 cm of soils in England and Wales by soil type and land use.