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 update estimates of subsoil organic carbon (OC) in England and Wales made by Bradley *et al*. (2005; *Soil Use Manage.* **21,** 363-369) using soil and land use databases, and compare the results with other published data. We estimate that the soils of England and Wales contain 11406, 980 and 433 Tg of OC at 0−30, 30−100 and 100−150 cm depths, respectively. Thus half of the soil OC is found below 30 cm depth. Peat soils account 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 have more than 25% of their profile OC per unit area in the 100−150 cm depth, whereas most other soils have less than 8% at this depth. The differences between soil types are consistent with differences in soil formation processes. Differences in depth distributions between land uses are small, but subsoil OC stocks in cultivated soils are generally smaller than in soils under grassland or other land uses. Data on subsoil OC stocks in the literature are scarce, but what there is broadly agrees with the findings of the above database exercise. There is little evidence with which to assess how subsoil OC stocks are 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 to 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).

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, focussing on the effects of soil type and land use.

Methodology

Database exercise

In outline, 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 (see below) 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 150cm deep and some are deeper. The details are as follows.

Spatial distribution of soil types and land use. The NATMAP, created by 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' (including unmanaged grassland, semi-natural vegetation and 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 characterise soil series during detailed field survey in 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 was 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:

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

where C is the OC stock per unit area (g m^{-2}), $\hat{C}$ is the OC content per unit mass (g kg^{-1}, determined on the < 2 mm fraction), S is the stoniness (kg kg^{-1}, 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 Groups distinguished by the SSEW (Table 1) under each land use:

$$\overline{C} = \frac{\sum_{j=1}^{n}\left(w_j C_j\right)}{\sum_{j=1}^{n} w_j} \quad (2)$$

where $\overline{C}$ 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:

$$w_j = \frac{A_j}{\sum_{j=1}^{n} A_j} \quad (3)$$

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

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

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 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 Organisation World Reference Base (WRB) system (IUSS-ISRIC-FAO, 2006). We used the same OC stock units, land use and depth categories and methods as above, 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 criteria 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). 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 (see below) 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 & 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 are small, though there are clear differences in the total stocks, which increase in the order cultivated land to grassland to other. These reflect, in part, difference in plant inputs of C and the intensiveness of soil disturbances due to management. The depth-distributions 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 have 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 have the smallest total OC stocks per unit area and more than 90 % of this is at 0–30 cm depth. Most soils have 50–60 % of their OC at 0–30 cm depth, except peat soils which have only 20 %, with about 30 % at 100–150 cm depth. Gley soils and pelosols have 12–17 % of their OC at 100–150 cm depth whilst others have less than 8 %.

These results are consistent with the processes of soil formation in different soils. Large subsoil OC stocks in periodically waterlogged gley soils 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 also accounts for elevated subsoil OC in podzolic soils. Surface-water gley soils have 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 to depth.

Total subsoil OC stocks

Table 3 shows the total OC stocks for the two countries subdivided by soil type and land use. Cultivated soils have smaller OC stocks at 30−150 cm depth (348 Tg) than soils under grassland (429 Tg) and other land uses (636 Tg). For cultivated land, the order from greatest to smallest stock at 30−150 cm depth is brown soils ≈ peat soils > surface- and ground-water gley soils > pelosols; for grassland it is brown soils > surface-water gley soils > peat soils > ground-water gley soils > podzolic soils; and for other land uses it is peat soils >> surface-water gley soils > brown soils > podzolic soils. The overall order across all land uses is peat soils >> brown soils ≈ surface-water gley soils > ground-water gley soils > podzolic soils ≈ pelosols.

The results reflect the differences in stock per unit area and the areal extents of the soils. Peat soils are 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 have the greatest areal extent (39 % of the total area) but have 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 are 1633 and 1143 Tg, respectively, which compares with 1209 and 870 Tg, respectively, reported by Bradley *et al.* (2005), i.e. our estimates are 35 and 31 % greater, respectively. The differences are due to the methodological differences outlined above. The differences are greater in the other land use(79 and 36 % more at 0–30 and 30–100 cm depths, respectively) than in cultivated land (16 and 22 %, respectively) and grassland (23 and 33%, 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.

Nonetheless we agree with Bradley *et al.* (2005) that around 40 % of soil OC in the top 100 cm of the profile is at depths greater than 30 cm. We estimate 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 3822 Tg in the upper 150 cm of the soils in England and Wales, of which half (1919 Tg) is 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), we found only eight studies giving depth-distributions of OC with less than 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 Supplementary Information SI 1 and a summary is given in Table 4.

In general OC stocks reported in the literature were comparable to 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. 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). Inevitably there were some local differences due to site-specific effects. Greater-than-average OC stocks were recorded for N-fertilised 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 reported 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-fertilised grassland than grassland not receiving N fertiliser 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 to more recent plantations, but lesser in a podzolic soil at a third site. 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 summarised in Table 5 and given in full in Supplementary Information SI 2. To the best of our knowledge, there are currently only two sites in England and Wales with published data on subsoil OC taken 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-characterised terrestrial sites in England and Wales under a range of land uses where, amongst others, OC is measured on both a five- (to 30 cm depth) and 20-year (to 120 cm depth) sampling cycle from 1993 (ECN, 2013). This data is 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). (Note that these estimates assume linear change over time, which may be erroneous over long intervals or following management changes – see 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 sequestration, 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 to 2006). Average annual accumulations of OC were up to 8 g m^{-2} in the upper 30 cm in soils not receiving N fertiliser. Only in soils receiving N fertiliser was there a reported 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 water content, 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 since 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 fertilisers 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).

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 the two countries (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). 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 have the largest OC stocks at depth. There is a general increase in soil OC stocks from cultivated land to grassland to other land uses reflecting, in part, differences in plant inputs and intensiveness of soil disturbances 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.

Acknowledgements

This work was funded by the UK Department for Environment, Food and Rural Affairs (Project SP1106 "Soil carbon: studies to explore greenhouse gas emissions and mitigation"). Rothamsted Research uses facilities funded by the UK Biotechnology and Biological Sciences Research Council. This paper is published with the permission of the Executive Director of the British Geological Survey (UK Natural Environment Research Council).

Supplementary Information

The following information is available with the online version of this paper:
SI 1 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.
SI 2 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.

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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)

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. SD = standard deviation.

Land use	Number of	OC stock per unit area (kg m^{-2})							Fraction of total 0−150 cm stock (%)		
Major Soil Group	soil series	0−30 cm		30−100 cm		100−150 cm		0−150 cm	0−30 cm	30−100 cm	100−150 cm
	n	Mean	SD	Mean	SD	Mean	SD	Mean			
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

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 Terrestrial raw soils and Raw gley soils

Land use	Area	Total OC stock (Tg)		
Major Soil Group	(km^2)	0−30 cm	30−100 cm	100−150 cm
Cultivated land				
Lithomorphic soils	3 769	38	2	1
Pelosols	5 332	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	6 171	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	3 810	45	2	0
Pelosols	2 607	27	18	6
Brown soils	26 670	248	127	23
Podzolic soils	4 876	65	30	5
Surface-water gley soils	18 077	195	104	33
Ground-water gley soils	4 664	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	2 232	33	1	0
Pelosols	681	7	4	1
Brown soils	10 322	94	45	8
Podzolic soils	6 098	114	33	5
Surface-water gley soils	9 850	152	80	21
Ground-water gley soils	2 206	31	14	6
Man-made soils	197	1	0	0
Peat soils	3 936	121	313	229
Total for land use	35 522	554	490	271
Total for England and Wales	145 644	1 633	1 143	506

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).

Land use Major Soil Group [WRB Reference Soil Group]	Location	Parent material	Depth (cm)	OC stock (kg m^{-2})	Notes	Reference
Cultivated land						
Pelosol [Luvisol]	Shelford, Notts.	Triassic mudstone	0-30 30-100	3.40 1.75	Soil under mixed arable use	Tye, 2010
Brown soil [Luvisol]	Broadbalk, Rothamsted, Herts.	Cretaceous chalk-with-flints	0-30 30-100	3.94 4.75	Long-term wheat with N-fertiliser	Poulton *et al*., 2003
Brown soil [Cambisol]	Sunk Island, E. Yorks.	Alluvium over Quaternary glacial and lacustrine sediment	0-30 30-100 100-150	10.16 8.41 4.55	Mean of two soils reclaimed from estuary	Ellis & Atherton 2003
Brown soil [Cambisol/Luvisol]	Shelford, Notts.	Recent head and alluvial sand over Triassic sandstone	0-30 30-100	7.12 6.06	Mean of five soils under mixed arable	Tye, 2010
Surface-water gley soil [Luvisol]	Shelford, Notts.	Triassic mudstone	0-30 30-100	3.19 1.62	Soil under mixed arable use	Tye, 2010
Ground-water gley soil [Fluvisol]	Sunk Island, E. Yorks.	Alluvium over Quaternary glacial and lacustrine sediment	0-30 30-100 100-150	6.49 10.33 4.57	Mean of two soils reclaimed from estuary	Ellis & Atherton 2003
Ground-water gley soil [Fluvisol/Gleysol]	Shelford, Notts.	Alluvial gravel, sand and clay over Triassic mudstone	0-30 30-100	8.42 2.06	Mean of four soils under mixed arable	Tye, 2010
Various	Several locations, England and Wales	NA	0-30 30-100	7.00 4.00- 5.00	All cultivated soils	Bradley *et al*., 2005
Permanent managed grassland						
Brown soil [Luvisol]	Park Grass, Rothamsted, Herts.	Cretaceous chalk-with-flints	0-15 15-30 30-100	5.20 3.55 5.13	Mean of three long-term treatments	Jenkinson *et al*., 2008
Brown soil [Luvisol]	Broadbalk Wilderness, Rothamsted, Herts.	Cretaceous chalk-with-flints	0-15 15-30 30-100	4.68 3.19 5.18	Grazed grass from natural regeneration	Poulton *et al*., 2003
Brown soil [Cambisol]	Sunk Island, E. Yorks.	Alluvium over Quaternary glacial and lacustrine sediment	0-15 15-30 30-100	4.66 4.61 11.47	Soil reclaimed from estuary	Ellis & Atherton 2003
Surface-water gley soil [Luvisol]	Palace Leas, Cockle Park, Northumb.	Carboniferous shale	0-15 15-30	6.25 3.43	Mean of four treatments, no N	Hopkins *et al*., 2009
Surface-water gley soil [Luvisol]	Palace Leas, Cockle Park, Northumb.	Carboniferous shale	0-15 15-30	12.72 2.87	Mean of two treatments with N	Hopkins *et al*., 2009
Various	Several locations, England and Wales	NA	0-30 30-100	8.00- 9.00 5.00	All permanent grassland soils	Bradley *et al*., 2005
Other land uses						
Brown soil [Luvisol]	Broadbalk Wilderness, Rothamsted, Herts.	Cretaceous chalk-with-flints	0-15 15-30 30-100	5.35 3.68 5.87	Coarse grasses from natural regeneration	Poulton *et al*., 2003
Brown soil [Luvisol]	Broadbalk Wilderness, Rothamsted, Herts.	Cretaceous chalk-with-flints	0-15 15-30 30-100	5.09 3.49 6.05	Regenerated mixed deciduous woodland	Poulton *et al*., 2003
Brown soil [Luvisol]	Geescroft Wilderness, Rothamsted, Herts.	Cretaceous chalk-with-flints	0-15 15-30 30-100	4.12 2.91 5.07	Mean of two soils under regenerated oak and ash woodland	Poulton *et al*., 2003
Brown soil [Cambisol]	Frilsham and Binfield, Berks.	Tertiary London Clay (with or without loess)	0-15 15-30	6.30 3.40	Mean of two soils under ancient oak woodland	Wilson *et al*., 1997
Brown soil [Cambisol]	Yattendon and Binfield, Berks.	Tertiary London Clay (with or without loess)	0-15 15-30	4.90 2.30	Mean of two soils under oak plantation	Wilson *et al*., 1997
Podzolic soil [Cambisol]	Bolderwood, Hants.	Tertiary Barton Sand	0-15 15-30	4.90 2.40	Ancient oak and beech woodland	Wilson *et al*., 1997
Podzolic soil [Cambisol]	Bolderwood, Hants.	Tertiary Barton Sand	0-15 15-30	6.90 2.50	Oak and beech plantation	Wilson *et al*., 1997
Raw peat soil [Histosols]	Moor House, Cumbria	Limestone bedrock and glacial till	0-30 30-100	4.70-17.60 2.10-31.90	Data from soils under moorland	Garnett *et al*., 2001
Raw peat soil [Histosols]	Broomhead Moor, S. Yorks.	Carboniferous Millstone Grit	0-30 30-100 100-150	11.00-28.70 25.60-66.90 18.30-47.80	Data from soils under moorland	Rawlins *et al*., 2009
Various	Several locations, England and Wales	NA	0-30 30-100	11.00-12.00 12.00-17.00	All semi-natural (vegetated) soils	Bradley *et al*., 2005
Various	Several locations, England and Wales	NA	0-30 30-100	10.00-12.00 7.00- 8.00	All woodland soils	Bradley *et al*., 2005

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 Soil Group	Location	Years of monitoring	Depth (cm)	Change in OC stock (g m^{-2} $year^{-1}$)	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		
Brown soil	Broadbalk Wilderness, Rothamsted, Herts.	1881-1904	0-15	+32.3	Wheat to mixed deciduous woodland	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		

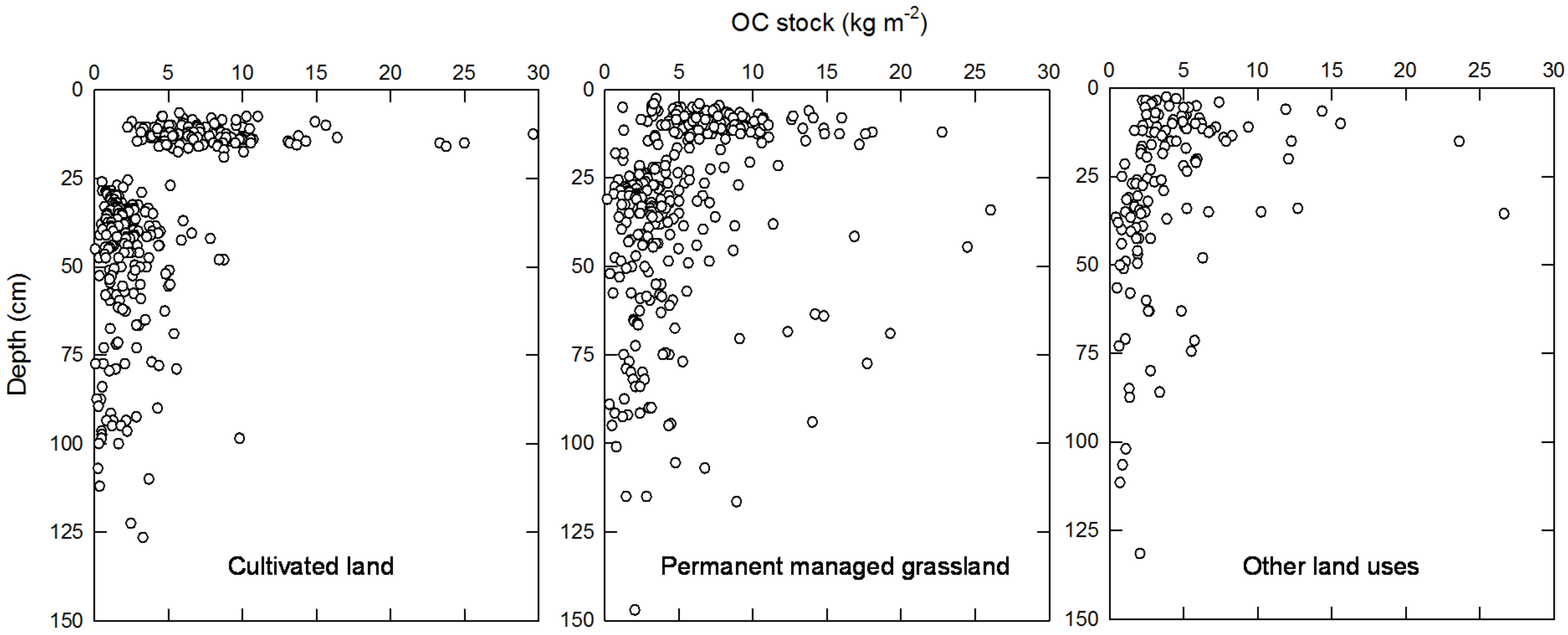

Figure 1 Depth distributions of soil organic C (OC) stocks per unit area from the Horizon Fundamentals dataset in LandIS for the main soil series in England and Wales calculated with Equation (1) and grouped by land use category.