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No change in topsoil carbon levels of Great Britain, 1978–2007

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Abstract

Soil is an important store of carbon (C) and there has been recent concern that accelerated loss of carbon from the soil may be reinforcing climate change. There is therefore a need to both track current trends in soil C storage and to identify how soil can contribute to carbon emission reduction targets. Countryside Survey (CS) is an integrated national monitoring program in which vegetation, topsoil, water and land use measurements are made across Great Britain (GB). The soil component of CS is unique as topsoil C concentrations have been measured at three time points (1978, 1998 and 2007) together with topsoil bulk density (2007 only), vegetation composition (all years), and land use (i.e. Broad Habitat, 1998, 2007). The combined dataset allows estimates of change in topsoil C stock over time and the influence of land use change on topsoil C to be investigated. Results indicate that although there was a small increase (8%) in topsoil C concentration between 1978 and 1998 and small decrease (6.5%) between 1998 and 2007, there was no significant change in GB topsoil C concentration (in $g\,kg^{-1}$), density (in $t\,ha^{-1}$) or stock (in Tg) between 1978 and 2007. Within individual habitats some consistent trends were observed and by examining plots which had consistent vegetation composition since 1978 we demonstrate that land use change was not responsible for the few significant changes that were found. These results are comparable with the few other estimates of recent topsoil C concentration and stock changes in W. Europe, with the exception of a previous study in England and Wales which reported significant topsoil C losses of up to 50% over a similar period. Possible reasons for the contradictory findings are discussed. An extra 220–730 Tg of C would be stored in topsoil C stocks if all GB soils were optimised at the top 5–25% C densities as recorded for each habitat in 2007.

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1 Introduction

Current awareness of global climate change has led to increased interest in the carbon (C) cycle and its effects on climate. It has been estimated that, globally, twice as much C is stored in soils as in the atmosphere, with peatlands contributing a third of this. Therefore, even small decreases in soil C stocks might contribute significantly to increased atmospheric CO_2 concentrations. Recent research has highlighted the vulnerability of soil C; changes in soil C stocks could be brought about by changes in either natural or managed inputs or outputs, through factors such as land use change (Guo and Gifford, 2002), management (de Vries et al., 2006), climate change (Smith et al., 2008), atmospheric deposition (Pregitzer et al., 2008) and changing CO_2 concentrations (Jastrow et al., 2005).

In light of the potential vulnerability of soil C, long-term in situ field monitoring is essential to assess whether soil C levels are changing, to evaluate the relative importance of factors controlling soil C stores at the large-scale, and to assess whether efforts to sequester C in soils are successful (Nisbet, 2007; Morvan et al., 2008). In the latter half of the 20th century, many European countries undertook surveys to assess the status and nature of their soil resources, and sufficient time has now passed to allow meaningful resampling of soils and the assessment of decadal-long changes in soil properties. However, there have been conflicting reports on changes in soil C from W. European surveys in recent years (e.g. Bellamy et al., 2005; Kirby et al., 2005; Goidts and van Wesemael, 2007; Stevens and van Wesemael, 2008). In particular, Bellamy et al., 2005 reported large losses of C from topsoils in England and Wales (in organic soils, up to 50% of original C lost in 25 years) and postulated a link to climate change since losses were geographically spread and irrespective of initial land use. Although this conclusion has been challenged (Smith et al., 2007; Potts et al., 2009), if repeated elsewhere, such losses have significant implications both for the permanence of soil C and climate change (Schulze and Freibauer, 2005),

Here we report estimates of topsoil C concentrations (in $g\,kg^{-1}$), C densities (in t ha^{1}) and stocks (in Tg) from the Countryside Survey of Great Britain (GB), which sampled soils across England, Scotland and Wales in 1978, 1998 and 2007. The Survey provides an independent dataset which allows the assessment of trends in topsoil C levels since 1978, the relationship to land use change to be examined, and potential for future storage to be estimated.

2 Material and methods

2.1 Countryside survey methodology

Countryside Survey uses a stratified random sample of the one-kilometre squares in GB, in which the stratification is the ITE Land Classification (Firbank et al., 2003). In its original formulation the Classification had 32 strata covering GB but has since been modified to 45 classes divided between Scotland, England and Wales. The original 1978 survey consisted of 256 1-km squares and collected five soil samples per square where possible, taken from random co-ordinates in five segments of the square. Detailed vegetation and other biophysical measurements were taken at the same location. In total, the 1978 survey collected 1197 soil samples for analysis. During 1998/99, surveyors collected soil samples from the plots used for soil sampling in the original 1978 squares; 1098 samples were returned for analysis. Plots were re-located using maps and/or markers placed in previous Surveys, with resampling at a location 2 m south from the original sampling location. In 2007, 591 1-km squares were sampled (Fig. 1) from May to November 2007 and a total of 2614 samples returned for analysis. More samples were therefore taken in 2007 than collectively in 1978 and 1998. Over time some vegetation plots have been replaced, usually due to access restriction by landowners, failure to satisfactorily re-locate plots, or loss of plots to urban development. In these cases new plots were located elsewhere in the square according to agreed statistical design criteria. Table 1 summarises the number of repeat and unique plots in CS to date. Statistical modelling (see below) enables the changing number

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and location of plots to be taken into account when estimating change over time. In 1978, soils were collected by trowel from the top 15 cm of the soil profile in a soil pit (ca. 200 g), whereas in 1998 and 2007 a plastic tube (15 cm deep × 5 cm dia.) was inserted into the soil to obtain a sample from a known volume.

2.2 Topsoil C concentration determinations

Soil organic matter (SOM) concentration was determined for every soil sample using loss-on-ignition (LOI) methods, which are suitable for SOM determinations in all soils. In 1978 and 2007, LOI was carried out on ca. 10 g of oven-dried soil at 375 °C for 16 h, while in 1998 LOI was initially determined on ca. 1 g oven-dried soil at 550 °C for not less than 2 h. It was subsequently found, using a sub-set of 40 1998 soils (data not shown) that the 1998 method resulted in significantly higher LOI values (+1.21±0.25%, $P < 0.001$) compared to the 1978/2007 method. To remove this effect of differing LOI methods, as many as possible of the 1998 soils were reanalysed using the 1978/2007 LOI method. In total 74% of the original 1998 soils were reanalysed; the remainder of the soils could not be analysed due to insufficient archive sample weight. Reanalysis of the soils reduced the average LOI values of the 1998 soils by 1.1%. The LOI values for the 1998 soils that could not be reanalysed were estimated from a regression equation derived from the samples that were analysed using both methods. In both 1998 and 2007, soil C content was determined by elemental analysis (EA), and the combination of LOI and EA results (data not shown) demonstrated that in both years 55% of SOM was accounted for by C; C concentration was therefore estimated for samples in all years (i.e. including 1978) using the equation:

$$\text{C concentration (g kg}^{-1}) = \text{LOI (\%)} \times 0.55 \times 10 \quad (1)$$

2.3 Bulk density measurements

Soil bulk density (BD) was determined for the first time in the 2007 Survey, using the same soil sample as for LOI determination. Bulk density was estimated for each soil sample by making detailed weight measurements throughout the soil processing procedure (Emmett et al., 2008). Briefly, the exact dimensions of the sampled soil core were recorded before the soil was extruded from the plastic tube, and the soil was then weighed, homogenised, re-weighed before drying at room temperature for up to two weeks. At the end of this period, the soil was again weighed and then sieved to 2 mm, and the weight and volume of the unsieved debris (largely composed of stones and plant material) recorded. A sub-sample of 10 g of soil was then accurately weighed and dried overnight at 105 °C, before LOI determination. The moisture loss at each stage of the process was used to estimate the initial moisture content of the soil, and from that the initial dry weight of the soil. Bulk density was then estimated using the equation:

$$\text{Bulk density (g cm}^{-3}\text{)} = \frac{\text{(dry weight of soil (g)} - \text{weight of unsieved debris (g))}}{\text{(volume of core collected (cm}^3\text{)} - \text{volume of unsieved debris (cm}^3\text{))}} \quad (2)$$

2.4 Topsoil C density estimates

Estimating soil C density requires estimates of both C concentration and BD, the latter of which was only measured in the 2007 Survey. However, there was a strong relationship between C concentration and soil BD in the 2007 data (Fig. 2) which could be applied to the 1978 and 1998 LOI data to estimate BD, and hence C density, in those years. To limit the accumulation of errors through applying successive empirical transformations to the data, the 2007 relationship between C concentration and C density (calculated directly from the 2007 data) was used to estimate C density from C concentration in 1978 and 1998.

Since BD was only measured in 2007 it is not possible to estimate or allow for any temporal autocorrelation between successive measurements of BD or C density on the same plot and this could lead to overestimation of significance levels in estimating change. To allow for this a random component was added to each estimated C density measurement to reproduce the degree of scatter in the graph of C concentration against C density for 2007. Thus any temporal autocorrelation in the estimated density values comes only from the autocorrelation of the concentration values. The significance levels for change in density are therefore conservative. To avoid potential bias arising from the use of measured density on one sampling occasion and estimated density on others, the same prediction method was applied to the 2007 C concentration data and all C density results reported here were produced using estimated density data for all survey years. Topsoil C density was estimated for each plot using the equation:

$$\text{Topsoil C density (t ha}^{-1}) = \text{C concentration (g kg}^{-1}) \times \text{bulk density (g cm}^{-3}) \times 1.5 \quad (3)$$

2.5 Statistical analyses

The sampling strategy used to obtain CS data is complex. The data sampling is hierarchical, with random placing of plots within randomly chosen 1-km squares within land classes, and plots are revisited for each successive survey. The data is further complicated by an increase in sample size with each survey and the inevitable occurrence of missing values, for example when plots are lost to survey or not relocated, or when samples are lost. To take account of this structure estimates of mean values and change reported in this paper have been produced by fitting a statistical model to the data and using the parameters of the fitted model to estimate quantities of interest. The model used is a repeated measures mixed-effect model containing random square and plot effects and an autocorrelation parameter of order one to allow for correlation between successive measurements on the same plot. This model (Scott, 2008) was chosen because it most accurately reflects the sampling structure of the data, allowing for its hierarchical structure and the repeated measurement of individual plots. It is also able to cope with incomplete observations and so utilises all available data i.e. data from both unrepeated and repeated plots. In addition, in order to make minimal assumptions about the data distribution and to avoid possibly unwarranted assumptions of normality, the confidence intervals used to estimate significance are produced using bootstrapping techniques (Efron and Tibshirani, 1993). For each analysis the dataset is randomly resampled many times and the model refitted to each of these bootstrap samples. The variation in the fitted model parameters then quantifies their precision. Average values for each of the three survey years and the changes between the years are estimated for each strata of the ITE Land Classification using the parameters of the fitted model. The parameters for individual strata are then combined to give estimates of regional or national status and change.

Prior to the 2007 Countryside Survey estimates were produced using non-modelling methods. Estimates of means for a particular survey were calculated using all the available data for that survey while changes between pairs of surveys were estimated from only those plots surveyed in both surveys. This inevitably lead to discrepancies between estimates of status and change since they were obtained from different subsets of the data. The modelling approach avoids this problem and produces estimates of status and change which are consistent across all surveys as well as fully utilising all the data. Since, however, the modelling approach is less transparent it was considered important to validate our findings and other methods of estimating change have been used as a check on the modelling results. With very few exceptions (due to convergence problems in model fitting and not within the soils data) differences between results from the fitted models and the alternative methods of calculation have been small, providing assurance that the modelling approach is effective as well as efficient. As an example the average change in C concentration from 1978 to 2007 across GB soils as a whole is estimated from the fitted model to be 0.05 g kg^{-1} yr^{-1} (se=0.12). The simple mean of the individual plot changes for just those plots that were sampled in both 1978 and 2007, i.e. ignoring all the data structure and all information from unrepeated plots, is 0.06 g kg^{-1} yr^{-1} (se=0.14). The modelling approach using all available data has increased the precision of the estimate somewhat but has not substantially changed its value. Both estimates are non-significant. As a result of these checks we are confident that the estimates reported here are robust to the choice of analysis method.

All data analyses were performed using SAS v9 or SAS Enterprise Guide 4 (SAS

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2.6 Reporting categories

Results are reported using a variety of categories. At the largest scale, we report summary results for GB, and for its three constituent countries, England, Scotland and Wales. Across GB, we report by two habitat classifications, Broad Habitats (BH) and the Aggregate Vegetation Classes (AVC) of the Countryside Vegetation System (CVS; Bunce et al., 1999). The CVS classification is a description of vegetation types produced from a quantitative hierarchical classification of the different plant species found in the CS sample plots, based on a statistical analysis of the field data (Bunce et al., 1999), and the AVC is a higher-level grouping of the CVS classes. Each plot had an AVC assigned to it in each survey year, based on the recorded vegetation composition. Since individual plots may change AVC over time, the AVC in each year was used in analysis. AVC results are presented in two ways; firstly all plots in each AVC category for each survey year, secondly, only plots which have been repeated since 1978 and which have not changed AVC. A comparison of these two approaches gives an indication of the potential role of shifts in AVC (i.e. a proxy for land use/management change) on observed trends in soil C. Since AVC is a plot-level category, national-level results cannot be produced from it, and upscaling to provide national-level estimates requires the use of the area-based BH classification.

The BH classification has been developed over the last 15 years and currently consists of 27 habitats which account for the entire land surface of Great Britain, and the surrounding sea (Jackson, 2000). In CS, the BH has a minimum mappable unit size of 400 m^2 (Carey et al., 2008). Since some broad habitats contain no soil, and others are rare and so not encountered frequently in CS, only 10 BH are reported here. Additionally, due to the lack of mapped habitat information in 1978, all reporting by BH refers to the 2007 habitat allocation for the parcel in which each vegetation plot resides, except when the plot was not sampled in 2007, in which case the 1998 BH allocation was used if available. In summary, the BH is a description of a parcel of land (e.g.

an arable field), whilst the AVC is a description of a plot within a parcel (e.g. a small patch of lowland woodland at the edge of an arable field); therefore the AVC may not be representative of the whole parcel, and may differ from the BH, but is representative of the vegetation above the soil sampling locations. BH areas in 2007 were taken from Carey et al. (2008).

Soils were also classified into four soil C groups: mineral (0–8 LOI%, or 0–44 g C kg^{-1}), humus-mineral (8–30 LOI%, or 44–165 g C kg^{-1}), organo-mineral (30–60 LOI%, or 165–330 g C kg^{-1}) and organic (60–100 LOI%, or 330–550 g C kg^{-1}) based on the mean C concentration of each plot over all survey years. Mean concentrations were used, and plots sampled only once across the survey years were excluded from this analysis, in order to avoid regression to the mean effects (see Discussion).

3 Results

3.1 Structure of topsoil C concentration data

Recorded LOI values were in the range 1.0–98.5%, corresponding to topsoil C concentrations of 5.5–541.8 g C kg^{-1} (data not shown). The maximum C concentration possible in a soil when using Eq. (1) is 550 g kg^{-1}; the distribution of C concentrations across the observed range is shown in Fig. 3a. The mix of soils across GB has a characteristic bi-modal U-shaped distribution pattern, with the majority of soils containing <100 g C kg^{-1}. Across the three Surveys mineral, humus-mineral, organo-mineral, and organic topsoils accounted for 34–39, 35–38, 6–7 and 17–21% of all samples, respectively. The 1998 Survey contained a greater frequency of soils with higher LOI values (Fig. 3b), which led to higher estimates of C concentrations in that year. We can find no systematic bias in our data (e.g. an undersampling of a particular habitat, soil type or geographical area) which could lead to this difference.

Within CS, 58% of samples (2843 samples) come from plots which have been sampled more than once. Therefore, 42% of samples come from plots only sampled once,

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primarily due to the many extra sampling locations in 2007 (Table 1). Some variation in C concentration in repeat plots would be expected due to occasional failure in re-locating the exact plot, soil heterogeneity, differences in sampling procedures across the Surveys, and real change over time. However, the vast majority of observed differences in repeat plots were small (Fig. 4); 83–91% of differences in repeat plots were <100 g C kg^{-1}. At the other end of the scale, 1–5% of all differences from repeat plots were >300 g kg^{-1}. Such large differences are highly unlikely to be due to real change in soil C concentration, and suggest that soils in some locations were extremely heterogeneous, or that surveyors were not always successful in accurately re-locating plots. There is no reason to expect such relocation errors to have a directional bias and it is clear from Fig. 4 that they occur symmetrically with respect to year. The net effect of such values will therefore be to add extra variation to the change data and hence reduce significance levels but not to bias or invalidate results.

3.2 Trends in topsoil C concentration

There were clear differences in average topsoil C concentrations between the constituent countries of GB (Table 2). Scotland, which contains the majority of the organic soils in GB, had the highest C concentrations and England, which contains a greater proportion of mineral soils, the lowest. Topsoil C concentrations in 1978 and 2007 were not significantly different for GB or any constituent country (Fig. 5a). Within soil C groups, there were significant increases in soil C concentration between 1978 and 1998 for mineral and organic soils; however subsequent declines in the period 1998 to 2007 led to no significant changes between 1978 and 2007 (Fig. 5b).

The pattern of higher C concentrations in 1998 compared with the other Survey years also occurred within many Aggregate Vegetation Classes and Broad Habitats, although changes were not always significant. Within AVCs, the only significant differences in topsoil C concentration between 1978 and 2007 were a decrease in arable soils (AVC crops and weeds) and an increase in all woodlands (the combined lowland and upland woodland AVCs). The overall picture is one of little large-scale change in topsoil C concentrations (Fig. 5c). In 1978, 1998 and 2007, CS sampled 23, 29 and 81 lowland woodlands, respectively, and 76, 71 and 198 upland woodlands. Coverage of these AVCs was low in both 1978 and 1998 due to the smaller number of samples taken in these years, and the infrequent occurrence of woodlands in the GB countryside. Larger areas of woodlands and greater numbers of soil samples collected have contributed to greater numbers of woodland soil samples in 2007. Our report of topsoil C concentration change in woodlands should therefore be seen in the context of low sample numbers in 1978 and 1998, and represents our best estimates based on available CS data. Amongst BHs, which represent the larger habitat unit within which each soil sampling location resides, topsoil C concentrations in 1978 and 2007 were significantly different in arable and horticultural, bracken, and broadleaf woodland soils. Note that the BH is based on 2007 recording (and occasionally on the 1998 data), since the BH classification did not exist in 1978. There were very low numbers of soil samples in the bracken BH in 1978 and 1998 – 10 and 12, respectively – so estimates for these years are likely to be inaccurate. The 2007 estimate, which is based on 53 samples, is more likely to represent a reasonable value of the C concentration in the bracken BH, and the significant change reported is likely an effect of better representation in 2007.

To remove the effects of large-scale vegetation/land use change, we also estimated topsoil C concentrations in plots which were sampled in all three Surveys, and in which the AVC did not change over time. Since the AVC of the plots are only known for the Survey years we cannot rule out changes in the intervening years (e.g. rotation between arable and grassland systems) but plots where the AVC has not changed are plots in which the vegetation composition has been largely constant in 1978, 1998 and 2007. Only 405 plots had consistent AVCs in the three Surveys, and because of this there were insufficient samples in the tall grass and herb AVC, and soils in this category were ignored. Additionally, the lowland and upland woodland AVCs were grouped into one category, all woodlands, due to the small number of samples in each category individually. Nevertheless, trends in these plots (Table 3) were broadly consistent with those observed for the whole dataset suggesting that shifts in AVC (i.e.

land use change) are unlikely to be a major factor in the observed changes in soil C concentration. It is interesting to note that the sub-set of plots with consistent AVCs across the Surveys (Table 3) generally exhibited higher soil C concentrations than the population as a whole (Fig. 6) suggesting that soils with lower C concentrations were also those which were more likely to undergo vegetation change (a proxy for land use change). There were two exceptions; crops and weeds, where plots with higher topsoil C concentrations underwent vegetation change, and woodlands where no distinction between the two groups could be made. Comparing trends over time, it is clear that changes in soil C concentration where AVC has not changed mirror those of the population as a whole (Fig. 6).

3.3 Topsoil bulk density

Topsoil bulk density in individual samples in 2007 ranged from 0.02 to 1.95 g cm^{-3}, and was negatively correlated with soil C concentration (Fig. 2), with mineral soils exhibiting the highest bulk density values and organic soils the lowest. Average topsoil bulk density across AVC and BH classes varied between 0.2 and 1.2 g cm^{-3} and was lowest in bog soils and highest in arable and horticultural soils (Table 4). However, within each AVC or BH large ranges of BD values were observed.

3.4 Trends in topsoil C density

Soil C concentration and BD data were combined to estimate topsoil C density (Table 5). Since the relationship between C concentration and BD is non-linear (Fig. 2), average C density cannot be calculated directly from average concentration and bulk density values; i.e. multiplying the values in Tables 2 and 4 using Eq. (3) will not produce the C density estimates in Table 5. Trends in C density were broadly similar to those observed for topsoil C concentrations but with fewer statistically significant results. Reasons for this likely include our conservative method of estimating C density in the earlier Surveys and the fact that the relationship between soil C concentration and BD (Fig. 2) led to topsoil C densities of the same magnitude regardless of soil C concentration.

Despite the range of C concentrations in GB soils, which vary by a factor of 300, the relationship between C concentration and BD was such that the mean topsoil C density of organic soils were only 1.7 times greater than that of mineral soils (Table 5). Topsoil C density of mineral soils increased in the period 1978 to 1998, and then decreased in the period 1998 to 2007, reflecting trends in C concentration data (Table 2). Within AVCs, the only significant change across the 29 year period was a reduction in topsoil C density in crops and weeds, which was also found in plots where AVC was constant (Table 6; Fig. 7). Where AVC was unchanged (Table 6), soils within the fertile grassland AVC exhibited a significant increase in topsoil C density in the period 1978 to 2007; however this was not reflected in data including the whole population (Table 5). Within BHs, the only significant change in topsoil C density between 1978 and 2007 was a mean reduction of 5.7 $t\,ha^{-1}$ in arable and horticultural soils, primarily occurring since 1998.

3.5 Trends in topsoil C stocks

The 2007 topsoil C density data were multiplied by the area of each country or BH to establish the total topsoil stock (Tg) contained in each unit. For countries, the only significant difference observed was an increase in topsoil C stock for England between 1978 and 1998 (Table 5). Within BH, since topsoil C densities did not differ greatly between habitats, total topsoil C stocks (Fig. 8) reflected the areas of each BH across GB; hence the largest topsoil stocks were contained in the BHs with the largest areas – arable and horticultural, improved grassland and bogs.

Although there were few significant changes in topsoil C density, there were significant changes in BH areas across GB in the period 1998 to 2007 (Carey et al., 2008). The combination of changes in area and C density results in changes in the total stock of topsoil C in each BH. We examined whether changes in BH area or C density had a greater influence on total C stock changes in each BH (Table 7). The reduction in the total stock of topsoil C in the arable and horticultural BH of 45 Tg between 1998 and 2007 was almost equally derived from the significant reduction of the area of this BH and from a significant reduction in C density. In contrast, the increase of total topsoil C stock of 13 Tg in improved grasslands was entirely due to the significant increase in the area of this BH over the nine years, despite a small reduction in C density. Only in shrub heath and bog habitats was the change in total C stock largely due to (non-significant) increases in topsoil C density and not to changes in area. In contrast, the significant increase in area of broadleaf, mixed and yew woodlands was offset by a (non-significant) reduction in topsoil C density. Nevertheless, these results suggest that for many BH, changes in habitat area had a greater influence on changes in total topsoil C stocks than changes in C density. It should be noted that in habitats where increases in area are accompanied by reductions in C density, these reductions may be due to soils with lower C density entering the BH and thus reducing mean density until soil C adjusts to a new equilibrium. Thus mean C densities are modified by the flow of land from one habitat to another. Despite this, combining change in topsoil C density and habitat areas suggests a non-significant net loss between 1998 and 2007 of 14 Tg C from topsoils at the GB scale for the 86% of GB land covered by these BHs. This is similar to the change estimated using the mixed model approach (mean loss 30 Tg; Table 5). These estimates vary due to the different methods used to estimate change, however both estimates of change represent only 1–2% of the total topsoil C stock of GB.

3.6 Potential of extra topsoil C storage in GB

What is the C storage potential for GB topsoils, if all soils were managed for C? To give a rough estimate of this value, we examined the mean C density in each BH and the C density of the 95th percentile of the data, and then multiplied these values by the area of each BH in 2007 (Table 8). Differences in C density between the mean and 95th percentile ranged from 26.2 t ha^{-1} in the arable and horticultural BH to 71.5 t ha^{-1} in the shrub heath BH; however when combined with the area of each BH, the relative

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capacity of habitats to store extra C was almost identical to the relative areas of each BH, and the four habitats each with the capacity to hold over an extra 100 Tg C were the four most extensive habitats in GB – bogs, neutral grasslands, arable and horticultural, and improved grasslands. If the 75th percentile was chosen instead of the 95th (i.e. a more conservative estimate of the ability of topsoils to store extra C), a total of 248 Tg of extra C could be stored, and the habitats with the greatest capacity were shrub heath (+38 Tg), arable and horticultural (+40 Tg) and improved grassland (+64 Tg; data not shown). These estimates rely on the untested assumption that the 75th or 95th percentile represents a C density that all soils in a BH could attain if managed correctly; in reality there are many factors which influence topsoil C density, including vegetation composition and climate and soil conditions, and some of these are outside human control. In addition, this calculation takes no account of changes in soil depth, peat accumulation rates or bulk density. However, this analysis suggests that two of the most intensively managed habitats in GB – arable and horticultural land, and improved grassland – perhaps show the most potential to store greater amounts of C, if the land was managed to encourage C retention. Annual UK industrial emissions of C are around 150 Tg; moving all soils to the C densities at the 75th and 95th percentiles would thus sequester 1.7 and 5.3 years worth of annual emissions, respectively.

4 Discussion

4.1 CS estimates of topsoil C stock

It is estimated that European soils contain 75–79 Pg C (Schils et al., 2008), of which UK soils store 6–7 Pg. The top 15 cm of soils in GB (i.e. the UK without Northern Ireland) store ca. 1.6 Pg C (Table 5). Soils are the largest terrestrial pool of C, and there is a need to track and understand trends in soil C, and to optimise future soil C storage through land management and use. Although measurements of topsoil organic C are available in all member EU countries, very few countries have repeated sampling

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campaigns (Saby et al., 2008) and to our knowledge, Countryside Survey is the first survey in Europe to sample soils three times. Moreover, CS data are obtained from a randomised sampling scheme, hence should be fully representative of the soils of GB, the analytical methods have been the same for each survey, and the results presented here are robust to variation in the method of statistical analysis. The approach to monitoring programs in Europe has been reviewed by Kibblewhite et al., 2008; Morvan et al., 2008 and Schils et al., 2008; current national monitoring programs are criticised for of lack of soil BD measurements, insufficient sample numbers and lack of repeated explanatory measurements. Countryside Survey, particularly the 2007 Survey, addresses these particular issues for GB.

4.2 Is C being lost from topsoils across GB?

The results from the Countryside Survey of Great Britain suggest that the topsoil C stock of GB and its constituent countries has not changed significantly since 1978. Likewise, topsoil C densities also remain unchanged, and although there were changes in C concentration between 1978 and 1998, and 1998 and 2007, significant changes from 1978 to 2007 were only detected in arable, bracken and woodland soils. Particularly significant in light of Bellamy et al. (2005) is the lack of change in topsoil C concentrations in organic soils; although this disagrees with Bellamy et al. (2005), it is in agreement with other reports and the outputs of soil C models. Possible reasons for this disagreement are discussed below.

4.3 Comparisons with other reports of topsoil C concentration changes

There are unfortunately few monitoring studies from W. Europe with which to compare our topsoil results; some studies only report changes in C concentration, some only C density, some only to 1 m depth. Of those suitable for comparison, estimates of change are compared with CS results in Table 9. Our results for changes in topsoil C concentrations in arable and grassland systems are comparable with the ranges reported by various studies on Belgian soils, but are smaller than those reported by Bellamy et al. (2005) for England and Wales. For woodland soils, CS estimates of C concentration change are larger than those reported from a major UK resurvey of 103 woodlands (Kirby et al., 2005), and in the opposite direction to reports of C changes in woodland soils in Belgium, and to that of Bellamy et al. (2005) for England and Wales. Given the small number of woodlands sampled in CS in 1978 and 1998, a potentially more accurate picture of changes in topsoil C concentration in GB woodlands was reported by Kirby et al. (2005), whose survey specifically examined changes in woodlands between 1971 and 2000–2003 and found no significant change in topsoil C concentration, which remained around 88 g C kg^{-1}.

4.4 Topsoil bulk density and C density

To our knowledge, our measurements of topsoil BD represent the most comprehensive dataset available for GB to date. Figure 2 compares our BD results with that of the pedotransfer function first used by Howard et al. (1995) and subsequently by Bellamy et al. (2005). For C concentrations greater than 68 g C kg^{-1}, the Howard et al. (1995) equation overestimates BD, especially at high C concentrations. Using the Howard et al. (1995) equation, soils containing >400 g C kg^{-1} are constrained to possess a BD of 0.22–0.28 g cm^{-3}, but CS results show that 92% of soils containing >400 g C kg^{-1} exhibit BD <0.2 g cm^{-3}, and 51% have a BD <0.1 g cm^{-3}. Very low BD for highly organic topsoils has been reported by other authors (e.g. Givelet et al., 2004; van der Linden et al., 2008). The differences in the two BD equations have implications for the estimates of topsoil C stock and change given by Bellamy et al. (2005). Our estimate of 949 Tg for the total topsoil C stock of England and Wales in 1978 is substantially larger than the 864 Tg estimated by Bellamy et al. (2005), however this is partly due to different conversion factors used; assuming that C is 50% of LOI (as Bellamy et al., 2005) rather than 55% (the value used here), CS data yields an estimate of 863 Tg C for England and Wales in 1978. However, the different BD equations produce estimates of C stock at specific C concentrations that vary considerably; Bellamy et al. (2005)

estimated that soils in England and Wales which contained >300 g C kg^{-1} in 1978 had a total topsoil (0–15 cm) C stock of 121.7 Tg. Using the more realistic CS equation to estimate topsoil C stock for these soils reduced this value to ca. 73 Tg, and on the same basis would reduce the estimated loss of C from these soils from 2.1 to ca. 1.2 Tg yr^{-1}. However, these revised estimates of topsoil C stocks do not explain the substantial differences between our results and those of Bellamy et al. (2005) in terms of change in topsoil C concentration and stock.

CS estimates of topsoil C density assume that the relationship between C concentration and BD in 2007 is the same in 1978 and 1998. Since there are no studies of changes in BD over time across the entire range of C concentrations, this assumption remains untested. A range of factors such as land-use specific effects (e.g. Chanasyk and Naeth, 1995; Jansson and Johansson, 1998; Prosser et al., 2000; Sharrow, 2007) and soil moisture variation (Hopkins et al., 2009) are likely to contribute to the large variation in BD at any given C concentration (Fig. 2), but given the large sample size and representative nature of CS data it is unlikely that the overall C concentration-BD relationship will change significantly over time.

The one consistent trend in topsoil C density was declines in arable soils, reflecting the C concentration results. Countryside Survey topsoil C density changes are similar to those of other W. European studies (Table 9), although there remains disagreement among the other studies, even for the same areas. CS estimates of changes in woodland topsoil C densities (12–30 g C m^{-2} yr^{-1}) are also similar to model estimates of European forest soils by Liski et al. (2002) and Nabuurs et al. (2003), which suggest net sequestration of 19 and 11 g m^{-2} yr^{-1}, respectively.

4.5 Causes of change in topsoil C concentration and density

A range of potential factors responsible for soil C change have been proposed, including climate change (Davidson and Janssens, 2006; Heimann and Reichstein, 2008), nutrient deposition (Magnani et al., 2007; Pregitzer et al., 2008), management prac-

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tices (Jones and Donnelly, 2004; Jones et al., 2006), increasing atmospheric CO_2 concentrations (Jastrow et al., 2005), and land use and land use change (Guo and Gifford, 2002). However, at the large scale the attribution of change is complicated by the presence of multiple drivers which can simultaneously affect the balance of C inputs (largely plant biomass) and outputs (mostly microbial respiration). Our results suggest that land use change (as measured by the AVC) is not responsible for the few significant observed changes in topsoil C concentration. Climate change is also unlikely to be the cause of change in topsoil C, since changes in temperature and rainfall across GB since 1978 have been insufficient to cause large-scale changes in mineral soil C concentration or density (Smith et al., 2007). Model estimates of climate change-related variation in C density for England and Wales are -0.01, +0.03 and +0.01%yr^{-1}, for arable, grassland and forest mineral soils respectively, if changes in net primary productivity (NPP) are included (Smith et al., 2007), and in fact CS estimates of change are much larger than these: −0.09 to −0.20, +0.10 to +0.14, and +0.18 to +0.39%yr^{-1} for all arable, grassland and forest soils, respectively, across GB. Since land use change and climate change may be excluded as primary drivers of change, and trends differ between habitat types, other habitat-specific drivers must be responsible for the long-term changes observed in arable and woodland soils. In arable systems, a continuing response to the intensification of farming practices may be a dominant factor in continuing losses of topsoil C (Stoate et al., 2001). In woodlands, changes in tree age structure and reduced harvesting are likely to be the main drivers of soil C concentration increases (Liski et al., 2002; de Vries et al., 2006). Efforts to attribute the observed changes are ongoing.

4.6 Comparison with Bellamy et al. (2005)

The only other available data concerning changes in topsoil C in England and Wales, and for organic soils in W. Europe generally, are those reported by Bellamy et al. (2005), from the National Soil Inventory of England and Wales (NSI-E&W), which was carried out in stages from 1978–1983 and again from 1994–2003, and therefore covers

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some of the same geographic area and time period as Countryside Survey. However, CS results are considerably different to those of Bellamy et al. (2005) and, given the overlap of the monitoring region, this requires further discussion. There are numerous differences between the two surveys. The structure of the survey used by Bellamy et al. (2005) is different to that of CS; Countryside Survey uses a stratified random sample of the land across GB, whilst Bellamy et al. (2005) used a fixed grid approach. A comparison of the relative power of these two approaches to estimate topsoil C stocks and change has recently been carried out (Black et al., 2008). In CS, soil is only collected from one location per plot, either by bag (1978) or plastic tube (1998 and 2007), whilst Bellamy et al. (2005) collected and bulked 25 small cores (2.5 cm diameter × 15 cm deep) from a 20×20 m area at each site. Relocation distance is within 2–3 m for CS and 20–50 m for Bellamy et al. (2005). The two studies also differ in their methods of SOC determination; CS used a consistent LOI method in all years, whilst Bellamy et al. (2005) used Walkley-Black determinations for all samples in their original survey (despite Walkley-Black methods not being appropriate for C concentrations >80–150 g kg^{-1}; Bellamy et al., 2005; de Vos et al., 2007) and a mixture of Walkley-Black and LOI in the resurvey (G. Kirk, personal communication, 2008). Both Surveys have a small number of repeat plots with large differences in C concentration that cannot be due to real changes in soil C. Such large differences in topsoil C concentrations appear to be a feature of topsoil C sampling rather than a problem specific to CS methodology, and as stated above may affect the significance of results but are unlikely to affect their magnitude.

Whatever the cause of the different results, the mathematical reason for the topsoil C losses reported by Bellamy et al. (2005) is clear. Figure 2 in Lark et al. (2006) is a scatter plot of C concentration in repeat plots in the NSI-E&W, upon which the results in Bellamy et al. (2005) were based. Since the majority of soils in this plot lie below the 1:1 line, i.e. most C concentrations in the resurvey were lower than in the original survey, topsoil C losses are observed. This figure also shows that in the NSI-E&W resurvey, the maximum C concentration was just below 500 g kg^{-1}, as expected us-

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ing the reported LOI method and a conversion factor of C concentration (%)=0.5×LOI. However, C concentrations in the original survey were up to 580 g kg^{-1}, with a single outlying high value of ca. 660 g kg^{-1}. If correct, this figure indicates that between 1978 and 1998–2003, the maximum observed C concentration of soils in England and Wales decreased by 14%, which suggests a fundamental shift in the properties of highly organic soils over this time period, and that no soils which contained >500 g C kg^{-1} in 1978–1983 did so in 1998–2003. The processes that might be responsible for such losses of C are unclear; since highly organic soils only contain organic matter, loss of C could only occur if the C content of organic matter decreased. In contrast to the results of Bellamy et al. (2005), maximum LOI values in CS in 1978, 1998 and 2007 were all ca. 98% and in all years for which we have data soil C accounted for approx. 55% of the organic matter present. There is no evidence therefore for a fundamental change in the maximum C content of organic matter in GB soils. A much more likely explanation of Lark et al. (2006) Fig. 2 is that some mathematical or analytical difference (Potts et al., 2009) between the two NSI-E&W surveys led to a dataset where the maximum possible soil C concentration was 580 g kg^{-1} in the 1978-1983 survey, but 500 g kg^{-1} in the 1994–2003 survey, and that the distribution of soils across these two different ranges has led to the conclusion that real change has occurred.

4.7 Limitations of Countryside Survey

Countryside Survey does have some limitations that need to be considered. The emphasis on topsoil measurements excludes changes in the soil C concentration at depth and thus total C stored throughout the profile. In only considering the topsoil, CS is similar to many other national surveys (e.g. Bellamy et al., 2005; Lettens et al., 2005a). Another limitation in CS (as with many other surveys) is the single assessment of soil type carried out in 1978. In this initial year, a soil pit was dug and the soil characterised using the standard British classification of the time. Analysis using one categorisation of the data is vulnerable to regression to the mean (Galton, 1886) when the category allocated to individual sampling units can change with time.

Regression to the mean is the statistical effect whereby for repeated measurements samples far from the mean on any sampling occasion will tend to be closer to the mean on other sampling occasions. Thus any report of a negative relationship between initial C concentration and change in C concentration should be treated with suspicion unless regression to the mean effects have been accounted for. The results reported by Bellamy et al. (2005) may be partially explained by this effect (Potts et al., 2009), and recent reports from Belgium (Goidts and van Wesemael, 2007), New Zealand (Schipper et al., 2007) and the Netherlands (Hanegraaf et al., 2009) all report a negative relationship between initial C content and C change (i.e. soils containing greater C contents in an initial survey lost C at greater rates), but none appear to have taken regression to the mean into account. Ideally, changes in soil C should not be reported as change relative to initial C status at all, or by soil type which has been recorded only once, as all such analyses are open to regression to the mean. Relating change to average C level over the period of change as reported here using the soil C categories usually corrects for the effect and is a simple way of overcoming the problem.

5 Conclusions

No large-scale changes in topsoil C concentrations, density and stocks at the GB scale between 1978 and 2007 were observed. Arable systems were the only habitats to show consistent change for both topsoil C concentration and density with losses of 10–13% and 5–11% respectively. When combined with change in habitat area, arable soils were responsible for a net loss of 45 Tg C in the period 1998–2007 which was offset by increases in other habitats resulting in an estimated net loss of 14 Tg C (<1% of total stock) at the GB scale since 1998. Managing land to enhance topsoil C stocks to the 2007 top 5–25% levels within each habitat could capture 248–796 Tg C, equivalent to 1.7–5.3 years of industrial emissions of C.

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Table 1. Number of plots sampled for soils during each Countryside Survey.

	Survey years			Total number of samples
	1978	1998	2007	
1978 only	277			277
1998 only		160		160
2007 only			1629	1629
1978 & 1998	119 →			238
1978 & 2007	166 →	→		332
1998 & 2007		184 →		368
1978, 1998 & 2007	635 →	→		1905
Total number of plots	1197	1098	2614	4909

Table 2. Topsoil C concentration (g kg^{-1}) in 1978, 1998 and 2007. The “all woodlands” category represents the combined lowland and upland woodland AVCs.

Survey year	1978			1998			2007			Significant changes		
	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	78–98	98–07	78–07
Country												
Great Britain	135.6	122.7	147.8	146.5	133.5	159.0	137.0	125.7	148.8	***	***	
England	74.4	63.3	85.5	79.7	68.6	90.7	75.6	65.0	86.0			
Scotland	238.5	213.0	264.9	257.8	234.1	284.1	242.0	220.2	266.5	**	***	
Wales	107.6	86.2	130.9	108.9	89.3	132.9	108.6	88.8	129.4			
Soil C group												
Mineral	29.8	28.5	31.1	32.7	31.4	34.0	30.2	28.8	31.5	***	***	
Humus-mineral	76.1	70.3	82.2	78.7	74.1	83.4	76.2	71.6	80.9			
Organo-mineral	252.1	224.1	278.3	268.2	244.5	295.0	232.2	206.4	256.6		*	
Organic	446.6	425.8	464.9	482.4	467.8	494.2	467.9	454.4	480.9	***		
AVC												
Crops & weeds	34.9	30.9	40.0	33.2	29.6	38.4	31.3	27.0	36.5		**	***
Tall grass & herb	53.6	38.1	80.0	46.3	36.8	55.5	47.0	38.3	56.8			
Fertile grassland	47.3	42.5	52.5	51.6	48.1	55.5	48.3	45.4	51.9	*	*	
Infertile grassland	62.4	56.5	68.8	69.6	63.5	76.7	66.1	61.2	71.3	*		
Moorland grass mosaics	218.6	186.3	248.3	242.0	214.0	268.6	225.8	204.9	245.3			
Heath & bog	371.0	342.9	395.9	412.7	391.6	432.3	389.8	369.5	409.9	***		
Lowland woodland	58.0	43.0	69.0	86.1	57.0	120.0	65.5	54.9	80.8	*		
Upland woodland	128.2	96.9	163.4	178.0	146.9	208.6	159.8	137.2	183.7	*		
All woodlands	103.7	77.4	130.2	143.0	119.2	167.5	130.9	114.1	150.1	**		*
Broad habitat												
Arable & horticultural	34.5	30.1	40.1	33.5	29.7	38.3	30.7	26.8	35.4		***	**
Improved grassland	56.4	50.1	64.5	58.3	53.8	63.6	56.9	52.9	61.5			
Neutral grassland	67.1	57.9	77.5	70.1	62.3	80.6	68.0	59.6	77.3			
Acid grassland	235.1	196.7	277.8	256.7	224.3	287.8	228.5	204.7	253.9		**	
Bracken	155.2	99.5	211.7	154.7	100.0	216.0	195.9	153.4	249.3		*	*
Shrub heath	305.3	262.7	348.4	298.7	262.1	335.2	284.9	254.4	316.9			
Fen, marsh & swamp	231.7	171.4	295.9	252.8	197.8	311.5	228.6	184.3	275.3			
Bog	411.8	381.1	440.2	449.9	427.9	472.2	432.9	410.2	451.3	**		
Broadleaf, mixed & yew woodland	62.4	44.4	82.5	102.2	79.6	129.7	88.7	74.1	105.8	*		**
Coniferous woodland	203.7	160.2	248.0	222.0	187.0	256.8	197.8	163.2	234.5	*		

Classical soil type was only recorded in 1978, and cannot be used in analyses due to regression to the mean (see Discussion). Analyses by AVC are based on the vegetation classification of the CS plot. Analyses by Broad Habitat are largely based on the 2007 Broad Habitat classification of the area of land in which the plot resides (see Methods). Significance levels: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.005$.

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Table 3. Topsoil C concentration ($g\,kg^{-1}$) in original 1978 plots which remained in the same Aggregate Vegetation Class in the 1998 and 2007 surveys. The "all woodlands" category represents the combined lowland and upland woodland AVCs.

Survey year	1978			1998			2007			Significant changes		
	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	78–98	98–07	78–07
Crops & weeds	28.9	24.8	33.0	28.2	25.1	31.4	25.1	22.2	28.4		***	***
Fertile grassland	50.9	43.2	61.7	55.5	49.8	61.7	54.8	48.9	61.9			
Infertile grassland	69.4	55.9	85.2	73.1	62.1	85.9	71.1	60.9	83.2			
Moorland grass mosaics	264.6	200.1	334.5	294.1	227.2	346.9	264.9	205.5	313.7			
Heath and bog	413.7	375.3	450.6	452.7	431.7	473.7	436.6	405.8	464.1	**		
All woodlands	80.0	50.5	121.7	139.4	100.0	186.4	146.5	94.2	206.9	***		**

Significance levels: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.005$.

Table 4. Topsoil bulk density in 2007, in g cm^{-3}.

	Mean	−95% CI	+95% CI	Range
AVC				
Crops & weeds	1.25	1.21	1.29	0.32–1.95
Tall grass & herb	1.05	0.99	1.12	0.26–1.82
Fertile grassland	1.03	1.01	1.06	0.21–1.70
Infertile grassland	0.88	0.85	0.91	0.11–1.62
Moorland grass mosaics	0.41	0.38	0.44	0.02–1.31
Heath & bog	0.21	0.18	0.25	0.02–1.70
Lowland woodland	0.82	0.74	0.89	0.18–1.43
Upland woodland	0.53	0.47	0.58	0.06–1.48
Broad Habitat				
Arable & horticultural	1.23	1.19	1.26	0.32–1.95
Improved grassland	0.97	0.94	0.99	0.17–1.70
Neutral grassland	0.90	0.86	0.94	0.04–1.52
Acid grassland	0.43	0.38	0.48	0.04–1.70
Bracken	0.43	0.36	0.51	0.03–1.01
Shrub heath	0.35	0.31	0.39	0.04–1.36
Fen, marsh & swamp	0.45	0.37	0.53	0.04–1.17
Bog	0.17	0.14	0.19	0.02–1.07
Broadleaf, mixed & yew woodland	0.78	0.72	0.83	0.06–1.66
Coniferous woodland	0.52	0.45	0.58	0.06–1.42

Analyses by AVC are based on the vegetation classification of the CS plot. Analyses by Broad Habitat are based on the Broad Habitat classification of the area of land in which the plot resides.

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Table 5. Topsoil C density and stocks in 1978, 1998 and 2007. Country estimates are total topsoil stock in Tg, all other estimates are topsoil density in $t\,ha^{-1}$.

Survey year	1978			1998			2007			Significant changes		
	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	78–98	98–07	78–07
Country: C stocks												
Great Britain	1568	1496	1644	1612	1539	1689	1582	1527	1639			
England	788	755	822	819	787	852	795	765	825	*		
Scotland	619	591	650	623	599	653	628	609	650			
Wales	161	151	172	169	154	185	159	152	165			
Soil C group: C density												
Mineral	50.6	48.9	52.4	54.2	52.2	56.2	51.2	49.5	53.3	**	**	
Humus-mineral	75.1	72.5	77.5	77.6	75.2	80.0	76.3	73.8	79.0			
Organo-mineral	98.8	89.4	109.0	97.0	88.9	104.6	99.7	93.2	106.1			
Organic	83.3	77.6	89.1	80.9	74.7	87.2	85.0	78.6	92.0			
AVC: C density												
Crops & weeds	50.9	48.5	53.3	51.1	48.5	53.8	47.9	45.8	50.1		**	*
Tall grass & herb	59.6	49.6	71.4	60.4	54.8	66.4	58.1	53.5	62.6			
Fertile grassland	60.8	57.7	64.2	65.9	63.2	69.0	62.6	60.7	64.4	**	*	
Infertile grassland	68.9	65.6	72.6	73.6	70.2	76.8	71.6	69.3	73.9	*		
Moorland grass mosaics	86.9	79.2	95.9	89.6	84.2	95.2	89.7	86.1	93.4			
Heath & bog	87.3	82.5	91.8	83.4	78.1	88.5	84.4	81.2	87.8			
Lowland woodland	64.9	54.8	76.7	70.7	61.4	80.2	68.3	62.1	75.2			
Upland woodland	76.1	67.7	85.4	83.5	78.9	89.2	84.7	79.9	89.5			
All woodlands	72.2	70.8	84.3	79.6	78.0	89.4	79.6	74.1	81.1			
BH: C density												
Arable & horticultural	53.0	49.6	56.7	51.9	49.7	54.3	47.3	45.2	49.7		***	***
Improved grassland	65.6	62.9	68.3	67.9	64.9	70.5	67.2	65.5	68.9			
Neutral grassland	65.4	61.5	69.6	71.7	67.5	76.1	68.7	65.7	72.0	*		
Acid grassland	91.6	80.2	104.0	88.9	81.9	96.2	90.7	86.2	94.9			
Bracken	73.4	62.4	94.7	99.3	82.6	122.0	84.7	76.7	93.9	*		
Shrub heath	84.2	77.6	90.3	83.9	78.1	90.0	89.8	85.1	94.4			
Fen, marsh & swamp	85.7	68.4	100.1	82.1	70.7	91.4	82.8	74.8	90.4			
Bog	83.4	78.4	89.0	81.3	74.3	88.8	85.6	80.3	90.6			
Broadleaf, mixed & yew woodland	65.9	58.2	75.1	76.9	70.2	84.3	73.0	68.8	77.1			
Coniferous woodland	83.7	74.2	93.0	84.1	76.4	91.5	81.4	76.4	86.1			

Classical soil type was only recorded in 1978, and cannot be used in analyses due to regression to the mean (see Discussion). Analyses by AVC are based on the vegetation classification of the CS plot. Analyses by BH are based on the 2007 Broad Habitat classification of the area of land in which the plot resides. Significance levels: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.005$.

Table 6. Topsoil C density ($t\,ha^{-1}$) based on the original 1978 plots which remained in the same Aggregate Vegetation Class in the 1998 and 2007 surveys. The "all woodlands" category represents the combined lowland and upland woodland AVCs.

Survey year	1978			1998			2007			Significant changes		
	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	Mean	−95% CI	+95% CI	78–98	98–07	78–07
Crops & weeds	51.4	46.3	56.8	48.8	44.7	53.6	46.2	42.4	50.3			*
Fertile grassland	62.8	57.2	68.4	69.0	63.2	74.6	69.9	63.8	75.8	*		*
Infertile grassland	71.0	66.6	75.7	73.8	68.8	78.6	72.9	67.9	78.6			
Moorland grass mosaics	81.7	71.8	91.4	91.8	78.2	105.2	80.8	72.2	91.1			
Heath & bog	84.7	78.8	91.5	84.6	77.5	92.1	78.8	72.7	85.4			
All woodlands	66.2	58.8	75.0	90.5	76.7	106.4	78.5	66.0	90.9	***		

Significance levels: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.005$.

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Table 7. Change in total topsoil carbon stock (Tg C) 1998–2007 examined by combining carbon density ($t\,C\,ha^{-1}$) and habitat areas (ha) in these Survey years. * indicates significant changes between 1998 and 2007.

Broad habitat	Area (000 ha)	1998 C density ($t\,ha^{-1}$)	Total C stock (Tg)	Area (000 ha)	2007 C density ($t\,ha^{-1}$)	Total C stock (Tg)	Change 1998–2007 Change due to area (Tg)	Change due to C stock (Tg)	Net change (Tg)
Arable & horticultural	5067	51.9	263	4608*	47.3*	218	−21.6	−23.3	−45.0
Improved grassland	4251	67.9	289	4494*	67.2	302	15.0	−3.0	13.4
Neutral grassland	2007	71.7	144	2176*	68.7	149	11.0	−6.0	5.6
Acid grassland	1503	88.9	134	1589*	90.7	144	6.9	2.7	10.5
Bracken	315	99.3	31	260*	84.7	22	−5.0	−4.6	−9.3
Shrub heath	1299	83.9	109	1343	89.8	121	3.4	7.7	11.6
Fen, marsh & swamp	426	82.1	35	392	82.8	32	−2.5	0.3	−2.5
Bog	2222	81.3	181	2232	85.6	191	0.7	9.6	10.4
Broadleaf, mixed & yew woodland	1328	76.9	102	1406*	73.0	103	5.5	−5.2	0.5
Coniferous woodland	1386	84.1	117	1319	81.4	107	−5.1	−3.7	−9.2
Total change (Tg)									−14.0

Total areas are different in 1998 and 2007 due to the changing areas each BH, the balance of which (14% of land in GB) is made up of the other 11 broad habitat categories for which there is not enough data available to estimate C stocks. Broad habitats are presented because of the area data associated with them. The net change of −14.0 Tg is different to the value given in Table 5 (−30 Tg) due to different methods of calculation. Both values were not significantly different to zero.

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Table 8. Topsoil C stocks for major Broad Habitats in 2007, compared with stocks if all soils were at the current 95th percentile for C density.

Broad habitat	Mean C density ($t\,ha^{-1}$)	95th percentile C density ($t\,ha^{-1}$)	2007 area (000 ha)	Total stock based on mean (Tg)	Total stock based on 95th percentile (Tg)	Difference in total C stock (Tg)
Arable & horticultural	47.3	73.5	4608	218	339	121
Improved grassland	67.2	103.3	4494	302	464	162
Neutral grassland	68.7	118.6	2176	149	258	109
Acid grassland	90.7	141.2	1589	144	224	80
Bracken	84.7	113.6	260	22	30	8
Shrub heath	89.8	161.3	1343	121	217	96
Fen, marsh & swamp	82.8	134.4	392	32	53	20
Bog	85.6	133.8	2232	191	299	108
Broadleaf, mixed & yew woodland	73	106.7	1406	103	150	47
Coniferous woodland	81.4	115.9	1319	107	153	45
Total						796

Table 9. Literature reports of measured changes in topsoil C concentration and density in W. Europe.

Land use	Region	Reference	Time period	Depth (cm)	Change	CS change 1978–2007
C concentration					($g\,kg^{-1}\,yr^{-1}$)	($g\,kg^{-1}\,yr^{-1}$)
Arable	Belgium	Goidts and van Wesemael, 2007	1955–2005	30	−0.05	−0.23 to −0.12
Arable	Flanders	Sleutel et al., 2003b	1989–2000	24	−0.18	−0.23 to −0.12
Arable and pasture	French mountains	Saby et al., 2008	1990–2004	30	−0.26	−0.23 to −0.12
Arable	England and Wales	Bellamy et al., 2005	1978–2003	15	−0.4	−0.23 to −0.12
Grassland	Belgium	Goidts and van Wesemael, 2007	1955–2005	30	+0.12	0.03 to 0.13
Rotational grassland	England and Wales	Bellamy et al., 2005	1978–2003	15	−0.4	0.03 to 0.13
Permanent grassland	England and Wales	Bellamy et al., 2005	1978–2003	15	−0.6	0.03 to 0.13
Woodland	S. Belgium	Stevens and van Wesemael, 2008	1955-2005	30	−0.15	0.37 to 1.09
Permanent woodland	S. Belgium	Stevens and van Wesemael, 2008	1955–2005	30	−0.19	0.37 to 1.09
Woodland	Great Britain	Kirby et al., 2005	1971–2001	15	+0.1	0.37 to 1.09
Deciduous woodland	England and Wales	Bellamy et al., 2005	1978–2003	15	−0.7	0.37 to 1.09
Coniferous woodland	England and Wales	Bellamy et al., 2005	1978–2003	15	−1.0	0.37 to 1.09
Upland heath/moorland	England and Wales	Bellamy et al., 2005	1978–2003	15	−1.8	0.25 to 0.65
Bog	England and Wales	Bellamy et al., 2005	1978–2003	15	−4.2	0.25 to 0.65
C density					($g\,m^{-2}\,yr^{-1}$)	($g\,m^{-2}\,yr^{-1}$)
Arable	W. Flanders	van Meirvenne et al., 1996	1947–1994	22–32	+23	−10 to −5
Arable	Belgium	Lettens et al., 2005a	1950–2001	30	−3	−10 to −5
Arable	W. Flanders	Sleutel et al., 2006	1947–2004	22–32	−19	−10 to −5
Arable	Wallonia	Goidts and van Wesemael 2007	1947–2005	30	−12	−10 to −5
Grassland	Belgium	Lettens et al., 2005a	1950–2001	30	+22	6 to 9
Grassland	Wallonia	Goidts and van Wesemael 2007	1947–2005	30	+44	6 to 9
Woodland	Belgium	Lettens et al., 2005a	1950–2001	30	+73	12 to 30
Woodland	S. Belgium	Stevens and van Wesemael 2008	1947–2006	30	−23	12 to 30

Values from Bellamy et al. (2005) are estimates from graphs. CS values are derived from the Aggregate Vegetation Class results; AVCs crops and weeds and tall grass and herbs = arable, AVCs fertile and infertile grassland = grasslands, and AVCs upland and lowland woodland = woodlands. The CS sampling depth was 15 cm. The change in C concentration reported by Kirby et al. (2005) was not significant.

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Fig. 1. Location of Countryside Survey 1 km-squares in 1978, 1998 and 2007. All squares were sampled in 2007; black squares were also sampled in 1978 and 1998.

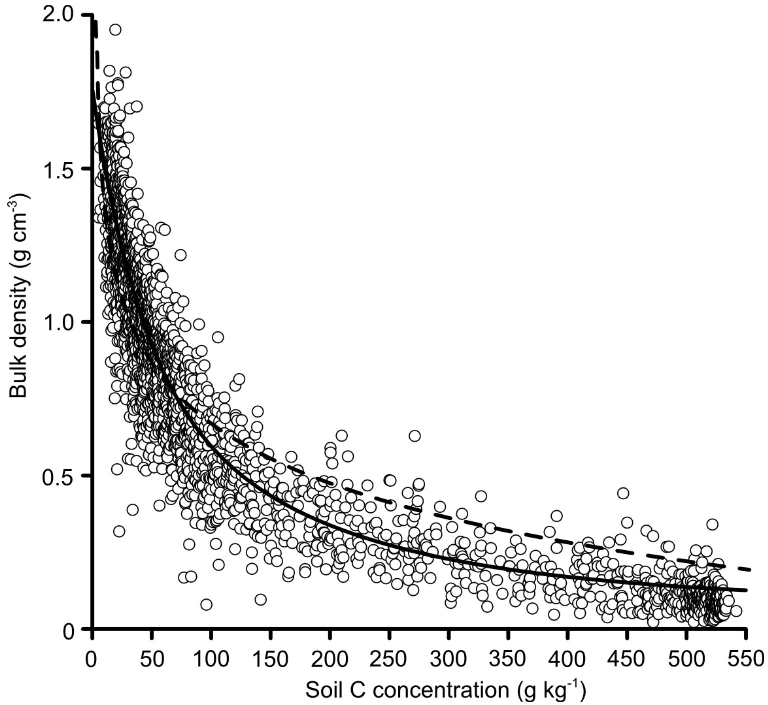

Fig. 2. Relationship between topsoil C concentration and bulk density in CS2007. Diamonds are estimates from Countryside Survey 2007, the solid line is the regression line of the data ($y = 0.89e^{(-0.025x)} + 0.77e^{(-0.006x)} + 0.1$), the dashed line is the estimate of bulk density derived from a commonly-used pedotransfer function ($y = 1.3 - 0.275\ln(x/10)$; Howard et al., 1995, as used in Bellamy et al., 2005).

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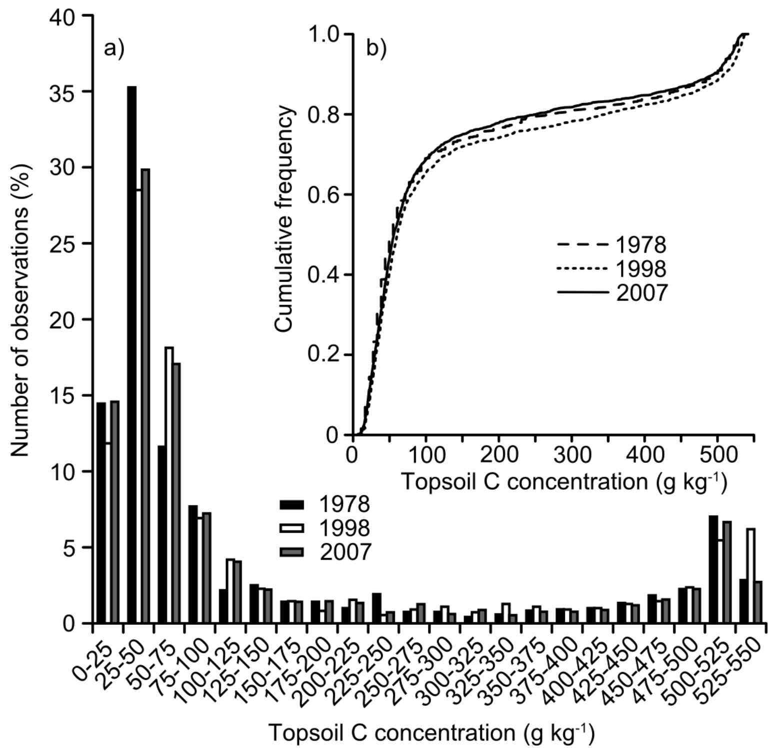

Fig. 3. Distribution of Countryside Survey topsoil C concentration data. **(a)** Number of observations for 25 g kg^{-1} divisions; **(b)** cumulative frequency.

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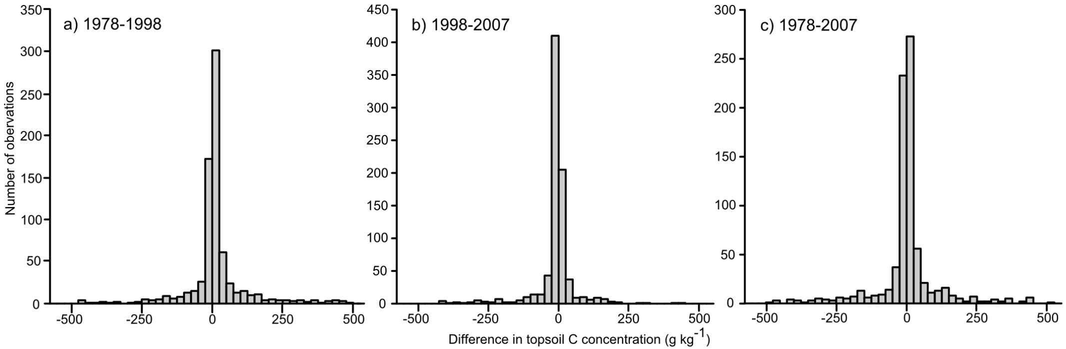

Fig. 4. Differences in topsoil C concentrations in repeat plots in the 1978, 1998 and 2007 Countryside Surveys. Note different y-axis scales.

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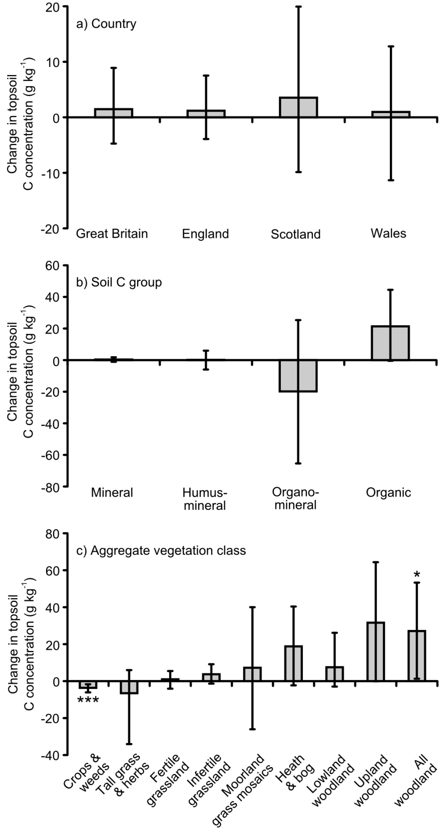

Fig. 5. Changes in topsoil C concentration between 1978 and 2007. Values are mean ±95% CI. Stars represent significant changes ($P < 0.05$). Although classic soil type was determined in 1978, results are not reported by this classification due to regression to the mean – see discussion for details.

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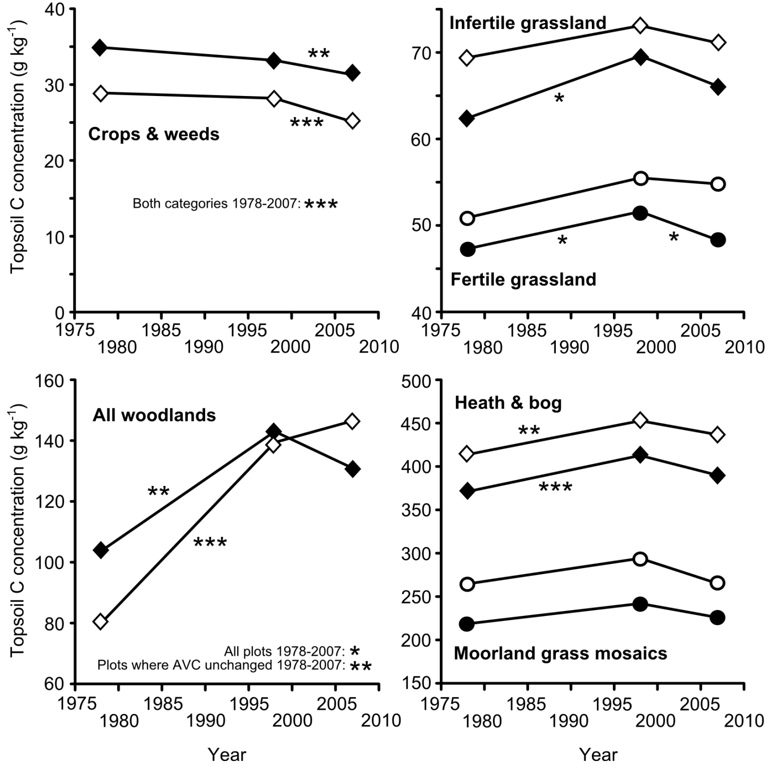

Fig. 6. Topsoil C concentrations in 1978, 1998 and 2007, for six Aggregate Vegetation Classes. Closed symbols represent all plots in the AVC for that survey year; open symbols represent plots present in all three Surveys which remained in the same AVC over time. Stars indicate significant changes between surveys: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.005$. Note the different y-axis scales.

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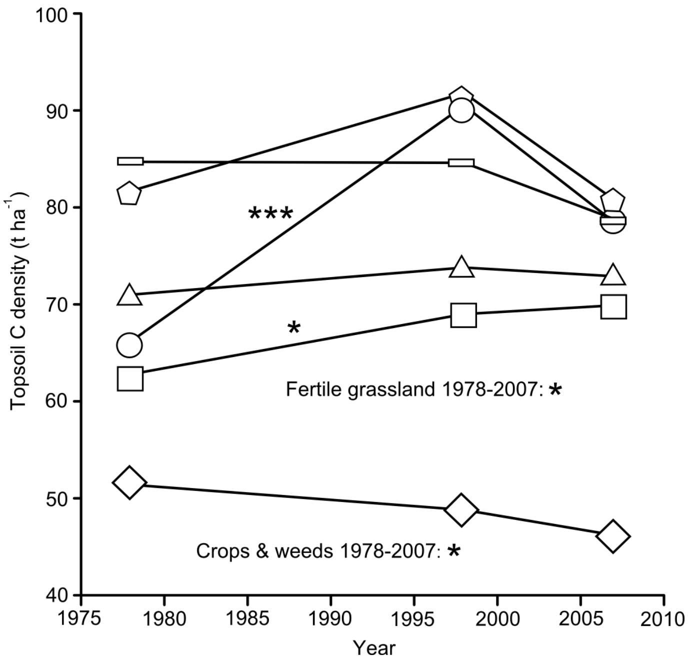

Fig. 7. Topsoil C density in plots present in the 1978, 1998 and 2007 Countryside Surveys which remained in the same Aggregate Vegetation Class over time; crops and weeds (diamonds), fertile grassland (squares), all woodland (circles), infertile grassland (triangles), moorland grass mosaics (pentagons), heath & bog (rectangles). Significance levels: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.005$.

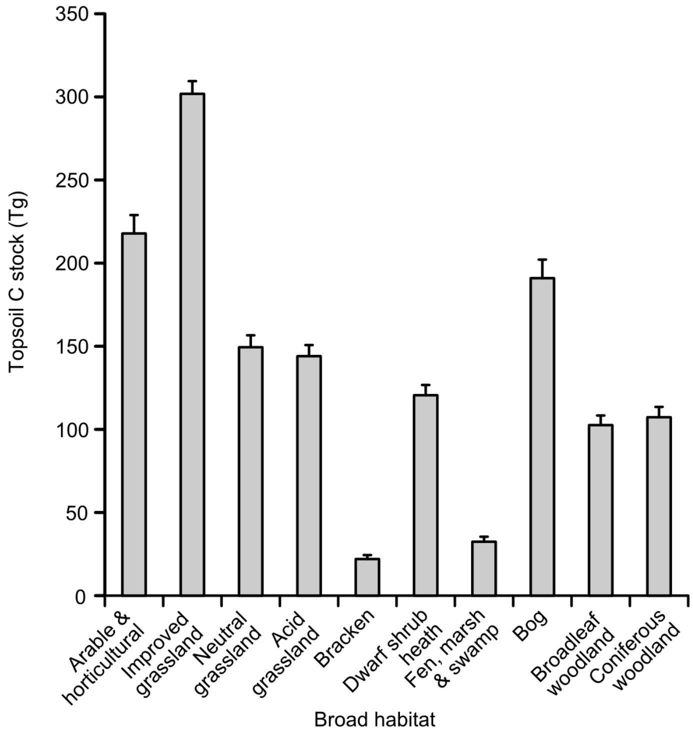

Fig. 8. Total topsoil C stocks in Broad Habitats across Great Britain in 2007. Values are mean +95%CI.

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