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Department for Environment, Food and Rural Affairs
Research project final report

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Sub-project iii: Review of the evidence base for the status and change of soil carbon below 15 cm from the soil surface in England and Wales

Executive summary

The world's soils contain more carbon (C), predominantly in organic matter (OM), than the atmosphere and terrestrial plants combined. Our knowledge of soil C is largely restricted to the topsoil, but more than half of soil C is stored at depths lower than 15 cm in the subsoil. Subsoil C represents a little-understood component of the global C cycle, with potential implications with respect to predicted changes in climate; it is important that the level of understanding of subsoil C in England and Wales is clarified and that potential knowledge gaps are identified.

The overall aim of this review was to evaluate the current status and dynamics of subsoil C in England and Wales by reviewing the best-available evidence and by sensible extrapolation. Further objectives sought to review the source and stability of subsoil C in general, to identify the key gaps in knowledge, and to seek evidence on how subsoil C may respond to imposed (soil management) or natural (climate change) changes in contributing factors in the future. Our methodology was to review the literature and to exploit the LandIS and Countryside Survey databases on soils and land uses.

Most soil C at depth in the profile is likely to be derived from exudates or other plant root materials as well as roots themselves. Some movement of surface C to the subsoil occurs in dissolved forms, by means of the soil fauna and by cultivation. Subsoil C is stabilised through different mechanisms, including chemical recalcitrance, adsorption to mineral surfaces and occlusion within aggregates.

The available data shows that Peat soils can have C contents exceeding 10% down to 1 m, equating to total stocks of over 7000 Mg ha^{-1}, representing a considerable repository of C. Surface-water gley soils, podzolic soils and shallow lithomorphic soils have greater C contents than brown soils and pelosols. There is some evidence that clay soils have more C than loamy soils. Lithomorphic soils, brown soils, surface-water gley soils and peat soils have greater C stocks in the subsoil under grassland and other land uses compared to arable land uses.

Evidence regarding grassland soils demonstrated that these often have a C content greater than 1% at 1 m depth, whereas arable soils have less than 1%. Grassland and semi-natural soils contain up to 200 Mg ha^{-1} in the upper 1 m compared to less than 100 Mg ha^{-1} in arable soils, although there is a large spread of data. Soils under ancient woodland are likely to be important stores of C. Where the same soil is under different management regimes, the regimes tend to affect total C in the upper part of the subsoil (to 45 cm), whereas C at greater depths is little-affected by surface vegetation. Small changes within the same general land use (such as different crops, fertilisation and tillage) can also affect soil C contents down the profile.

The current evidence on subsoil C dynamics suggests that there is no significant change in soil C contents and stocks below 30 cm under long-term arable or long-term grassland, but there is only data available for two sites at present. The main changes in soil C under both stable and changed land uses have been felt in the topsoil. Converting arable land to grassland or woodland, on the one site in England and Wales for which data is currently available, has caused an increase in the C stock of up to 0.5 Mg ha^{-1} yr^{-1} in the uppermost 80 cm depth of soil. It is likely that land use changes have masked any possible climate-change-induced changes in subsoil C.

In conclusion, we estimate that there is 980 Tg of organic C in the 30-100 cm depth of soils in England and Wales, representing a considerable store of C. Although largely dependent on the soil type, with peat soils being particularly important, land use does have an effect on subsoil C contents. Total subsoil C contents probably change very slowly over time when a change occurs, such as a change in land use, although evidence from isotope studies suggests that a quicker response can be seen in certain C compounds. There is very little evidence from which to assess the current dynamics of subsoil C in England and Wales, but what evidence we do have suggests that subsoil C contents under long-term arable or long-term grassland are stable. How changes in climate will affect subsoil C remains unknown, although some effect might be expected if there is a both a vegetation response to climate change and a definitive link between surface vegetation and subsoil C. Future assessments of the status and dynamics of subsoil C will benefit from a standardised C quantification method, the systematic sampling at the Environmental Change Network sites, and advances in modelling.

1. Introduction

Carbon in soils below 15 cm: subsoil C

The world's soils contain more carbon (C) (1200-2400 Pg, where 1 Pg = 10^{15} g), predominantly in organic matter (OM), than the atmosphere (720-750 Pg) and terrestrial plants (550-835 Pg) combined (Whittaker 1975; Batjes 1996; Jackson et al. 1997; Schlesinger 1997; Reicosky et al. 2000; Lal et al. 2001; Weil & Magdoff 2004). The equilibrium C content of soils, where inputs largely equal outputs, is mainly controlled by how they are managed. For instance, agricultural soils under grassland tend to have a greater C content than arable soils due to the difference in the management of the surface vegetation between the two systems (Johnston et al. 2009). Knowledge on soil C is largely restricted to the uppermost layer as this is the part of the soil profile that is more readily accessible and most obviously influenced by the inputs and losses of C in their interaction with the atmosphere and biosphere (King et al. 2005). Accordingly, national soil monitoring schemes have been based on samples collected from the topsoil, typically the upper 15 cm of the profile. The current estimate for the organic C content in the upper 15 cm of all soil in England and Wales is of the order of 850–950 Tg (where 1 Tg = 10^{12} g) (Bellamy et al. 2005; Emmett et al. 2010).

However, more than half of soil C is stored at depths lower than 20 cm in the subsoil (Batjes 1996; Jobbágy & Jackson 2000). Bradley et al. (2005) estimated that the total stock of C in soils in England and Wales at depths of 30-100 cm was 870 Tg. The processes that lead to such an accumulation are poorly understood however (Chabbi et al. 2009). Subsoil C stocks may be particularly important in certain soil types in England and Wales, such as peat soils. How soil management at the surface affects C in the subsoil is rarely considered, let alone understood. Perhaps even more poorly-understood than simply the status of subsoil C are the dynamics, both with respect to continued long-term soil management, and where a significant change in management occurs. Subsoil C, along with all other soil properties, is also presumably controlled in part by inherent soil-forming factors including parent material, climate and topography in addition to vegetation. The time-consuming and arduous task of sampling the subsoil is almost certainly one reason for the scarcity of information on subsoil C relative to topsoil C.

The importance of organic matter as a key property controlling soil quality has long been recognised, and the link between soil C and the global C cycle with respect to predicted changes in climate continues to receive significant attention. Subsoil C represents a little-understood component of the global C cycle (Jenkinson et al. 2008). It is therefore important that the current state of our understanding of subsoil C in England and Wales is clear and any knowledge gaps are identified. Important issues include how current soil management practices have affected the status and dynamics of subsoil C at present, and how subsoil C might respond to any changes in controlling factors, either natural or imposed, in the future.

For the purposes of this review we use the term "subsoil" to refer to that part of the soil profile deeper than 15 cm, which is the zone of interest in the review[1]. In addition, when referring to C we specifically mean organic C. Most soil C is organic but inorganic C, usually derived naturally from carbonate-rich parent materials or by adding lime, can be a significant component in some soils. Batjes (1996) estimated that of the total global soil C stock, excluding litter, in the upper 1 m (2293 Pg), approximately two-thirds was organic (1548 Pg) and one-third was inorganic (748 Pg).

Scope

The remit of this sub-project from the outset was to summarise the nature and processes associated with C through the soil profile in general, and to review the existing data on the content and change of subsoil C in order to evaluate the current status of subsoil C in England and Wales. Furthermore we sought to identify the key gaps in knowledge and evidence on how subsoil C may respond to imposed (soil management) or natural (climate change) changes in contributing factors in the future. We hoped to offer suggestions on safeguarding subsoil C where appropriate.

Aim and objectives

The overall aim was to evaluate the current status and dynamics of subsoil C in England and Wales by reviewing the best-available evidence and by sensible extrapolation. The four specific objectives, which directed the approach, were to:

1. Critically review the existing evidence base on the source and stabilisation of subsoil C in general.
2. Critically review the existing evidence base on the current status of subsoil C in England and Wales, supported by studies from elsewhere where appropriate.

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[1] The depth of topsoil (and therefore the depth at which subsoil begins) in a soil profile varies in the literature, typically ranging from 15 cm to 30 cm. Therefore, in this review we have referred to the specific depths determined as topsoil and subsoil in the research reviewed.

3. Critically review the existing evidence base on the dynamics of subsoil C in England and Wales, supported by studies from elsewhere where appropriate.
4. Evaluate the current status and dynamics of subsoil C in England and Wales by using sensible extrapolation from the evidence base.

Approaches

Literature reviews

The reviews of the evidence base on the nature of subsoil C in general and its current status and dynamics were largely conducted through ISI Web of Knowledge literature searches and searches of published reports. Whilst the focus always remained on data on soils from England and Wales, we expanded our searches to include studies from sites outside of England and Wales where the results would be relevant in terms of similarity of soils, climate and land use.

In summarising the evidence, we converted the data to common units. For the current status of subsoil C we have presented both the content (%; g C 100^{-1} g soil) and the stock (Mg C ha^{-1}, where 1 Mg = 10^6 g, or 1 tonne ("metric ton")) where possible. The link between the two is given by:

$$C_i = c_i \times \Delta z_i \times \rho_i \times 10000$$

where subscript i indicates the ith depth, C_i is the C stock per unit area in a soil depth interval (Mg ha^{-1}), c_i is the C content per unit mass (Mg Mg^{-1}), Δz_i is the soil depth increment (m), and ρ_i is the bulk density (Mg m^{-3}). It is important to note that an areal stock is specific to a particular soil layer. The total C content per unit area is found by summing depth intervals.

For the dynamics, we have divided the change in C by the number of years to get an annual change in content (‰ yr^{-1}; g C kg^{-1} soil yr^{-1}) or change in stock (kg C ha^{-1} yr^{-1}). Note that the units for the dynamics differ from those of the status by at least an order of magnitude for clarity of reading. Following the approach of others (e.g. Bellamy et al. 2005) we assumed a linear change with time. For a true estimate of C dynamics (and current status to a lesser extent) it is vitally important that the bulk density is measured (Smith et al. 2007). Poulton et al. (2003) and Jenkinson et al. (2008) developed an "equivalent depth" adjustment factor, defined as "the depth to which a soil sample should have been sampled to at time t so that it contained the same mass of soil at time t=0". This can result in a discrepancy between the C contents (unadjusted to density changes) and the C stock (adjusted to density changes), but this kind of approach means that changes in the stock of soil C between different sampling points can be compared with confidence.

It is important to reiterate that we have presented total organic C contents. Where the literature only reported total C data, we assumed that this was entirely organic and have made a note. Similarly where the evidence gave the OM content, we estimated that 58% of this was C (the van Bemmelen factor, Nelson & Sommers 1996), and all in an organic form by definition, and have made a note. Where C contents or stocks in the literature were presented in a figure rather than a table, we manually measured the value and have made a note.

Other information that has been noted from the literature, where reported, includes location, soil type, soil texture class, parent material, land use, year of measurement, depth, C quantification method, and the reference. More specifically we have given the soil type to the Soil Group level in the classification system of the Soil Survey of England and Wales (SSEW) (Avery 1980; see Table 1 for descriptions of the Major Soil Groups) and also the Reference Soil Group of the current "global" classification system – that of the Food and Agriculture Organization (FAO) (IUSS-ISRIC-FAO 2006) – or the United States Department of Agriculture system (Soil Survey Staff 1999). Broad land use descriptions were used to classify the soil data into arable, grassland, semi-natural and woodland land uses. The literature presented C contents and stocks in different depth increments and, as previously stated, definitions of subsoil are inconsistent. We have concentrated on those depths of 15 cm and beyond, but have also included surface horizon (topsoil) data where given for comparison.

The LandIS database

The data from literature reviews is very useful for estimating the current status of subsoil C in England and Wales at particular sites. In order to extrapolate point-source C data to estimate the current status for the whole of England and Wales we require systematic datasets on the distribution of the main soil types and land uses to complement this. In outline, we obtained information on soil C contents, bulk densities and stoniness at different depths from data for representative soil profiles for the different soil series–land use combinations in England and Wales held in the LandIS database (www.landis.org.uk; Proctor et al. 1998) maintained by the National Soil Resources Institute at Cranfield University. We obtained the spatial distribution of soil series–land use combinations across the two countries by overlaying the 1:250000 National Soil Map (Mackney et al. 1983) and the 1:100000 Countryside Survey Land Cover

Map for 1990 (Fuller et al. 1993), and finding the area of each series–land use combination in 1 km grid squares. We followed broadly the same methods, with some modifications, as Bradley et al. (2005) who produced a subsoil C stock map for the UK as a whole for a previous Defra project (SP0511).

The 1:250000 National Soil Map gives the distribution of 296 soil associations, each comprising between one and eight soil series which are found together within particular landscapes. We created a soil series dataset at 1 km resolution by integrating the fraction of each soil association within each 1 km square with the fraction of the soil series within each soil association. To determine the soil–land use combinations in each square, we obtained the fraction of each land use category in each square using the 1:100000 Countryside Survey Land Cover Map for 1990, and then multiplied the coverage of the soil series by the coverage of the land use. We used the three land use categories specified in the LandIS database: cultivated land (mainly arable and rotational grassland); permanent managed grassland; and 'other' (which include the semi-natural and woodland types classes used to arrange the literature review).

The representative soil profile data were obtained as part of the Soil Survey of England and Wales during the late 1970s and early 1980s from approximately 2500 soil profiles. We used data for each soil series–land use combination on organic C content, stoniness and bulk density. We collated the data by standard depth intervals, namely 0–30, 30–100 and 100–150 cm. Where horizons straddled a boundary between depth intervals, the data were apportioned between the depths *pro rata*. Litter horizons were included.

The organic C stock per unit area in each soil depth interval was calculated using the same expression given above, as adjusted to take the stoniness into account. To calculate the stock in a 1 km square for each soil series–land use combination, we multiplied the C content per unit area by the fractional coverage of the square with the soil series and the fractional coverage with the land use. In cases where the mapping exercise produced a soil series–land use combination for which there was no representative soil profile data (indicating that this series–land use combination should not occur), we populated the dataset as follows: for arable we used permanent grass data firstly and, if that did not exist, then with the data for 'other'; for permanent grass, firstly with 'other' and then arable; and for 'other', firstly with permanent grass and then arable. Note that we were only able to use the LandIS database to estimate the current status of subsoil C in England and Wales and not the dynamics.

Table 1. The Major Soil Groups of the soil classification system for England and Wales (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 organic carbon, depending on the clay content of the mineral fraction.

2. Review of the source and stabilisation of subsoil C in general

The source of subsoil C

Plant roots

The rooting characteristics of plants have been shown to influence the distribution of C in soil profiles through direct emplacement (Jobbágy & Jackson 2000; Salomé et al. 2010). Roots release C to the soil in the form of soluble organic compounds known as exudates and sloughed-off root cells (Jenkinson & Coleman 2008; Kalbitz & Kaiser 2008). Chabbi et al. (2009) suggested that the greater C content in subsoil preferential pathways, compared to the surrounding matrix, originated from roots which had exploited the favourable physical conditions. Salomé et al. (2010) reported that microbial communities in the subsoil processed relatively more compounds commonly found in root exudates than did topsoil communities, which provides indirect evidence for plant roots as a source of C in the subsoil. Plant roots are often associated with fungi in a symbiotic relationship whereby the fungi provides the plant with

nutrients and the plant supplies the fungi with C. Arbuscular-mycorrhizal fungi, where the fungi actually inhabits the cells of the plant root, in particular are believed to be an important pathway for the subsequent transfer of C to from plant to soil (Johnson et al. 2002).

Different plants allocate their biomass differently, with some vegetation types containing more above-ground biomass (e.g. trees) and others favouring more below-ground biomass (e.g. grasses) (Meersmans et al. 2009). Arable crops and trees tend to have deeper roots than grass species (Gregory 1988). In this way, land use has an influence on root-derived sources of subsoil C. In their study, Jobbágy & Jackson (2000) found that vegetation type had an influence on the vertical distribution of C down the profile, being associated with deeper depths under shrubland, intermediate for grassland and shallower depths for forest on a relative basis. Cereal crops have deeper roots than grasses, and have been associated with increased storage of C of a younger age (Don et al. 2009), although grassland soils commonly have greater C contents (Johnston et al. 2009). Poulton et al. (2003) found that reversion from arable to woodland continues to increase subsoil C a century after the change was made, and was correlated with increased root biomass. Carter & Gregorich (2010) found that a change from cereal crops to deep-rooted tall fescue in Canada brought about a small but significant increase in subsoil C after seven years. Some of the increase was linked to light-fraction and particulate OM, that is to say less-decomposed OM with a stronger resemblance to the original plant material. Lavania & Lavania (2009) described the merits of *Vetiver*, a vigorous growing Indian perennial grass whose roots can reach 2 m within 6 months, as a strategy for increasing subsoil C contents through the processes described above.

Dissolved C transport

Rooting is unlikely to be the sole source of subsoil C as there is often a discrepancy between root biomass and soil C, in that the latter is found at deeper layers than the former (Jobbágy & Jackson 2000; Baisden & Parfitt 2007; Carter & Gregorich 2010). At Rothamsted, Richards & Webster (1999) found that dissolved organic C made up a greater proportion of total organic C in the subsoil than in the topsoil in the arable treatments of the well-characterised Broadbalk experiment, although the fraction of total C was less than 2%. In finding a greater amount of C, and C of a young age, in pedological vertical "tongues" that resembled a preferential flow pathway rather than the surrounding matrix in the profile of a soil in France, Chabbi et al. (2009) suggested that part of subsoil C must be transported in dissolved forms. Ellerbrock & Gerke (2004) concluded similarly after measuring greater amounts of C on subsoil aggregates exteriors rather than interiors, when compared to topsoil aggregates, meaning that adsorbed C probably derived from the soil solution. Meersmans et al. (2009) found that the C decline with depth was less in sandy soil than finer-textured soil, which they suggested indicated greater transport of C through the profile in permeable soils. Important in all this is soil structure, which tends to be better-developed and more stable under grassland than under arable treatments. The soil pore network provides a potential route for surface C to be rapidly conveyed to the subsoil, and could be important in well-structured soils. In soils with well-developed macroporosity and preferential flow pathways, C may be transported in particulate or colloidal forms (Jacobsen et al. 1997; Don et al. 2009; Etana et al. 2009).

The evidence suggests that soil acidity is an important factor in dissolved C transport, and this is often linked to land use. Jenkinson & Coleman (2008) stated that more dissolved C moved down the profile in an acidic woodland soil than a calcareous woodland soil, and that organic C was less prone to leach downwards in grassland soils. Don et al. (2009) also stated that movement to the subsoil in dissolved forms is likely to be more important in woodland soils (which tend to be more acidic) than arable and grassland soils. Kalbitz & Kaiser (2008) in their work on a forest soil in Germany estimated that the contribution of dissolved C to subsoil C ranged from 22-50% depending on whether the dissolved fractions were largely sorbed to mineral soil or precipitated by Al respectively. Spielvogel et al. (2008) proposed that dissolved OM was the primary source of mineral-stabilised C in the subsoil.

There is conflicting evidence on the importance of dissolved C transport however. Jobbágy & Jackson (2000) in their widespread study found that as rainfall increased, subsoil C decreased which, they concluded, would not be expected if dissolved C transport was dominant. Kalbitz & Kaiser (2008) stated that fluxes from the topsoil to the subsoil decrease in importance with depth due to degradation of the C compounds in solution, sorption and precipitation. Richards & Webster (1999) also thought that decomposition of dissolved organic C at the surface meant that little was available for transport to the subsoil.

Soil fauna

Despite considerable work on dissolved C in recent years, several authors have suggested that the soil fauna appear the most likely means by which surface C is transported to lower depths. Elzein and Balesdent (1995) compared convective (i.e. dissolved transport) and diffusive (bioturbation) models and found that that the latter was a much better statistical fit to soil profile C data than the former. In many soils only a few faunal groups are found in the subsoil, particularly earthworms, and more specifically anectic forms (such as the common earthworm *Lumbricus terrestris*) that are deep-burrowing (Newman 1988). Earthworms may rapidly transport fresh C at the surface to deeper layers, although their importance in controlling subsoil C contents has occasionally been challenged (Jobbágy

& Jackson 2000). O'Brien (1984), in measuring radiocarbon (the radioactive C isotope which decays at a known rate and which is used to date organic materials), suggested that earthworm movement best explained the distribution of C in soil profiles in New Zealand. Land use and soil type influence soil fauna. It is generally the case that earthworm biomass and activity is greater in grassland soils than arable soils (Newman 1988; Riley et al. 2008) and greater in neutral clayey soils compared to acidic sandy soils (Don et al. 2009). Ellerbrock & Gerke (2004) reported in a forest soil that animal burrows at depth were enriched in C which they believed to resemble topsoil C compounds that had been transported. The C that has passed through the gut of soil fauna is typically more readily available to microorganisms such as fungi and bacteria (Newman 1988).

Soil management

As soil management controls the nature of the surface vegetation, it could be argued that the mechanism of direct placement of C by roots is wholly controlled by soil management. In addition, ploughing of arable soils results in the movement of near-surface C to the bottom of the plough layer and hence into the top of the subsoil (Don et al. 2009). Cultivation may also decrease soil C contents by fragmenting soil aggregates which exposes inaccessible OM to oxidation and microbial attack (Tisdall & Oades 1982). Beldini et al. (2010) found an increase in the proportion of C found inside microaggregates in a sandy soil converted from native forest to managed short-rotation forest, though the same was not found in a clay soil. This somewhat surprising result might be explained by the increase in clay content down the profile in the sandy soil and the availability of sorption sites within microaggregates (Beldini et al. 2010).

Parent material

Organic-rich soil parent materials across England and Wales, such as clays and shales, have organic C concentrations of up to 6% which contributes C to the subsoil through weathering and microbial assimilation. Unpublished data from the British Geological Survey show that profiles of organic C concentrations through soil and into underlying Oxford and Kimmeridge Clay increase at depths greater than 1 m. Oxford Clay, for instance, typically has an OM content of 5% (Norry et al. 1994). Kerogen, a mixture of organic compounds, is often found in sedimentary rocks. Previous studies have shown that soil microbes can assimilate fossil C from organic-rich bedrock types (Petsch et al. 2001).

Related to soil parent material is soil profile development over time. Carbon that was once found in the topsoil can effectively become subsoil C in time as the soil develops above. In England and Wales, soils have typically formed over the last 10000-18000 years since the peak of the last glaciation. Verheijen et al. (2009) estimated that the natural soil formation rate in Europe ranges from 0.3 to 1.4 Mg ha^{-1} yr^{-1}. Combining the two produces a crude estimate that the total soil formation to date in England and Wales would be of the order of 3000-25000 Mg ha^{-1} although it is important to stress that this does not take erosion losses into account.

The stabilisation of subsoil C

Chemical recalcitrance

Chemical recalcitrance has long been thought of as the main reason behind long-term stabilisation of soil C (Jobbágy & Jackson 2000; Ashman et al. 2003), particularly subsoil C. There is much evidence that compounds such as lipids (heterogeneous compounds of fatty acids and oils that are components of cell membranes), waxes and hydrophobic (water-repelling) compounds in soils have some degree of resistance to breakdown (Eusterhues et al. 2005b). The contribution of complex compounds such as aryl, carbonyl and O-alkyl C (aromatic and double-bond hydrocarbons) has been found to increase at depth whereas other compounds (such as single-bond alkyl C hydrocarbons) decrease (Eusterhues et al. 2007; Spielvogel et al. 2008). Dümig et al. (2009) found an increase in aromatic C and a decrease in O-alkyl and alkyl C with depth in a soil with a long-term history of fire. Black C (part-combusted C deriving from human activity) has been found to have a long residence time in the soil (Marschner et al. 2008). However, other experimental work suggests that subsoil C is no more chemically recalcitrant than topsoil C (Fontaine et al. 2007), even with lower levels of oxygen (O_2) (Salomé et al. 2010), and that there is no selective preservation of certain compounds commonly thought of as recalcitrant, such as lignin (commonly from the woody tissue of plants) and lipids (Marschner et al. 2008). Certain compounds of a younger age and thought of as more easily-degradable, such as microbial-derived carbohydrates (e.g. O/N alkyl-C) and polysaccharides, can be stabilised through other mechanisms, particularly mineral adsorption (Eusterhues et al. 2003; Rumpel et al. 2010) in preference to more complex aromatic alkyl C and plant-derived lignin (Spielvogel et al. 2008). Fresh C can be sequestered and stabilised by native hydrophobic C compounds in the soil (Spaccini et al. 2002). It has been found that the same substrate may be degraded at one site, but not at another (Ekschmitt et al. 2008). By studying the isotopic signature, Salomé et al. (2010) reported that carbon dioxide (CO_2)-C released at the beginning of an incubation experiment from subsoil samples was very similar to that of the surface vegetation, indicating rapid decomposition of fresh C deriving from roots.

6

Physical protection within aggregates

The idea that C gets physically protected within stable aggregates is common (Ashman et al. 2003; Marschner et al. 2008; Beldini et al. 2010; Sanaullah et al. 2011), and this is perhaps the most likely single explanation to emerge as to how C is stabilised in all parts of the soil profile, including the subsoil. Bossuyt et al. (2004) found incorporation of both fresh and old C in stable microaggregates in the presence of earthworms. Although focussing on mineral adsorption, Eusterhues et al. (2007) found evidence that C could be occluded in soil aggregates. Salomé et al. (2010) found that disturbing soil samples (by sieving) significantly increased organic C mineralisation. Smaller aggregates may provide more protection than larger aggregates as the former tend to have smaller pores (Bachmann et al. 2008). Soil structure and aggregation controls the supply of water, nutrients and O_2, and also controls the intimacy between C and potential decomposers (Eusterhues et al. 2007; Kuka et al. 2007; Bachmann et al. 2008). Jasinska et al. (2006b) found that in a forest soil, more C was found in aggregate interiors than exteriors, which they suggested could indicate physical protection remote from microorganisms. By contrast, no such C gradient was found in aggregates from an arable soil, although a decrease in microbial biomass was found in aggregate cores (Jasinska et al. 2006b). Others have reported preferential C adsorption to aggregate exteriors (Amelung et al. 2002). Complementary work found that aggregates were dominated by hydrophilic (C=O) rather than hydrophobic (C-H) groups, but that both groups were slightly more prevalent on aggregate exteriors rather than in interiors in a range of arable and grassland soils (Jasinska et al. 2006a). Most of the above work is based on destructive testing which in some way separates the field structure into natural aggregate fractions.

Physical protection on surfaces

Soil C, which tends to be part of negatively-charged OM compounds, may adsorb to the positive charges of hydroxyl groups on soil surfaces (Eusterhues et al. 2005b) and complex with metal oxides and hydroxides (Kleber et al. 2005; Bachmann et al. 2008). In this regard, the clay content of soils is important (Eusterhues et al. 2005b; Don et al. 2009; Meersmans et al. 2009). An increase in the proportion of C that is mineral-bound C with depth has been observed in some soils, and such C tends to be of an old age (Eusterhues et al. 2003; Spielvogel et al. 2008; Schulze et al. 2009). Correlations have been found between mineral-bound microbial-derived polysaccharides (such as galactose and mannose) and iron (Fe) and aluminium (Al) oxide content in subsoil fractions and that such C was highly-stable and old compared to non-microbial polysaccharides (Spielvogel et al. 2008; Rumpel et al. 2010). More recently however, radiocarbon dating has suggested that mineral-sorbed subsoil C may in some instances be of a younger age than bulk soil C which might mean that C is stabilised in other ways, such as aggregation, or that younger C adsorbs to mineral surfaces (Eusterhues et al. 2007). Added C residues can become associated with the fine mineral fraction relatively quickly in subsoils (Sanaullah et al. 2011). In addition, the method adopted (hydrofluoric acid) may also demineralise aggregate-protected C in addition to the mineral-sorbed C fraction intended (Eusterhues et al. 2003).

Others have also recognised the importance of Fe oxides and stabilised C in some soils, such as podzols (Kleber et al. 2005; Eusterhues et al. 2003; Eusterhues et al. 2005a; Eusterhues et al. 2005b; Spielvogel et al. 2008). Specifically, poorly-crystalline Fe oxides are believed to be important (Kleber et al. 2005). In a study on forest soils it was found that the majority of all mineral-bound C was associated with Fe oxides, which became more important at depth (Eusterhues et al. 2005a). It was believed that the Fe oxides created the available surface area with which the C (in OM) could bind (Eusterhues et al. 2005a) although it is important to note that these experiments were performed on sandy acidic soils with low clay contents. Chabbi et al. (2009) found that older C in the subsoil matrix was mainly stabilised on minerals, as found by using acid to demineralise such associations. Ellerbrock & Gerke (2004) found that coatings of C on aggregates in the subsoil contained hydrophobic substances which contributed to their stability.

For the most-stable fraction bound to clays and oxides, the availability of sorption sites and the presence of inorganic competitors for the sites are important considerations (Schneider et al. 2010). Schneider et al. (2010) found that more-recalcitrant carboxylic and aromatic compounds may be preferentially sorbed to Al hydroxides but only where the availability of surfaces was low.

Anaerobism

Fungal decomposition of organic C has been found to be limited to the topsoil as O_2 is required for the reaction, although bacterial decomposition can occur at depth (Ekschmitt et al. 2008). Meersmans et al. (2009) found a positive relationship between C and water content, although the water status of soil is also linked to texture. Sanaullah et al. (2011) reported that subsoils can remain up to 70% saturated throughout the year. Where aggregates have a saturated core and an aerated exterior, this can slow the diffusion of both the substrate from inside the aggregate to the surface and also the movement of any enzyme into the aggregate (Bachmann et al. 2008). The model of Kuka et al. (2007) was based on C protection in water-filled pores and they suggested that microorganisms require aeration as well as wetted surfaces. Despite this, it has been argued that some subsoils can have an abiotic environment that is more conducive to microbial decomposition (Sanaullah et al. 2011).

Lack of fresh C inputs

A recent development of the recalcitrance theory is that the acquisition of energy from old C cannot sustain microbial activity in the absence of a supply of fresh C (Fontaine et al. 2007), and that the stabilisation of C might be due to the lack of fresh C (Marschner et al. 2008). Certainly it is established that microbial biomass is significantly lower in the subsoil than the topsoil (Salomé et al. 2010). Chabbi et al. (2009) found that lignin in preferential pathways in subsoil, which contained more C and C of a younger age, contained lignin that was in a more-decomposed state than that in the adjacent matrix which was dominated by older C. Richards & Webster (1999) found that the potential for denitrification in subsoil in the laboratory was great, which indicated that a viable microbial community is ready in the subsoil to expand and exploit fresh substrate.

Despite the recent support for this "priming" effect from Fontaine et al. (2007), it is difficult to be confident with explanations derived from *ex situ* laboratory experiments where the physical characteristics of the soil were altered. Indeed Salomé et al. (2010) found no such priming effect and suggested that root-derived C was in the form of soluble molecules that are able to diffuse away from microbial degraders. Salomé et al. (2010) believed that the use of cellulose as the priming substrate by Fontaine et al. (2007) probably caused the dominance of fungi which, through hyphal spread, increased the interaction between the decomposer and the substrate. The priming effect, in the absence of continued supply of fresh C, is temporary (Fontaine et al. 2007).

Nature of the microorganisms

In their review Ekschmitt et al. (2008) reported that most decomposer organisms had limited motility and that it could be their physical and biochemical constitution which prevents the utilisation of some C substrates. As such, C stabilisation is neither due to recalcitrance nor physical protection (Ekschmitt et al. 2008). Bacterial utilisation of C substrates appears to be limited by short-distance transport processes and can take place at depth provided all necessary reaction partners are present (Ekschmitt et al. 2008). Sometimes a microbial community has to adapt if it is presented with substrate of a type it is not used to (e.g. subsoil communities receiving fresh C inputs) (Sanalullah et al. 2011).

Summary

Ignoring inorganic C from geogenic sources, such as carbonate C and fossil organic C weathered from bedrock, the ultimate source of the vast majority of soil C is surface vegetation. The evidence suggests that most soil C through the profile is directly derived from exudates and substances from plant roots complemented by movement of C from the surface by soil fauna. However, the profile pattern of soil C does not directly reflect that of root biomass C and hence there must be some movement of surface C to the subsoil either through dissolved forms (particularly in acidic soils), or by soil fauna (in neutral or alkaline soils). Cultivation can translocate surface C within the plough layer.

Subsoil C is stabilised through different mechanisms. It is true to say that some subsoil C has an inherent chemical recalcitrance, and that this might become more important at depth. However there is substantial evidence to suggest that C is more commonly stabilised in the subsoil through adsorption to mineral surfaces and occlusion within aggregates, distant from microorganisms, and that such C may not necessarily be chemically recalcitrant or of great age.

3. Review of the current status of subsoil C in England and Wales

Evidence of the current status of subsoil C in England and Wales

Estimates derived from the LandIS database for the total C stock for each soil type to the Major Soil Group level are given in Table 2, and the results combined by land use are given in Table 3. It is important to note that the C stocks per unit area are mean values for the Major Soil Group, which reflects the full range of all the contributory soil series.

Most C is found in the 0-30 cm depth, in all soil types and land uses. However, considerable C stocks are found below 30 cm. Peat soils are the dominant soil type in terms of C stock, having over 4000 Mg ha^{-1} in the 30-100 cm layer. Soil C stocks generally increase as the land use moves from arable to grassland to other (which includes semi-natural and woodland).

The estimated total soil organic C stocks in England and Wales for 0–30 cm and 30–100 cm depths are 1406 and 980 Tg, respectively, which compares with 1209 and 870 Tg obtained by Bradley et al. (2005). Our methods differed slightly from those of Bradley et al. (2005). Whereas Bradley et al. used just the dominant five soil series in each 1 km square, we used all the series. Since the Bradley et al. exercise, the representative soil profile data in LandIS has been extended (Hollis et al. 2006) and there are now fewer series without data. In addition we included data to 150 cm

depth and included C in unconsolidated subsoil ("C") horizons. Nevertheless, our new data agree with Bradley et al. (2005) that around 41% of all soil C is stored below 30 cm in the profile.

Table 2. Estimate of the C stock in the upper 150 cm of soils in England and Wales by Major Soil Group under cultivated land (predominantly arable but also rotational grassland), permanent managed grassland, and other (including semi-natural and woodland) land uses.

Major Soil Group	Area (km^2)	Organic C stock per unit area (Mg ha^{-1})			Total organic C stock (Tg)		
		0-30 cm	30-100 cm	100-150 cm	0-30 cm	30-100 cm	100-150 cm
Arable land use							
Lithomorphic soils	3470	346	39	31	34.59	1.81	0.92
Pelosols	4284	254	60	37	36.27	23.03	10.52
Brown soils	17335	192	48	17	115.67	68.61	16.66
Podzolic soils	688	395	94	30	8.19	4.09	0.84
Surface-water gley soils	10253	229	48	24	78.25	46.85	17.00
Ground-water gley soils	5489	417	132	98	67.74	44.98	23.12
Man-made soils	163	175	89	80	0.84	0.07	0.02
Peat soils	692	2744	4435	4853	25.38	57.44	32.04
Grassland land use							
Lithomorphic soils	3403	389	94	95	40.09	1.97	0.36
Pelosols	2207	321	75	34	23.16	14.91	4.98
Brown soils	22415	323	74	28	208.31	106.11	19.23
Podzolic soils	4001	633	97	27	52.87	24.67	4.02
Surface-water gley soils	15845	1149	98	71	171.17	91.37	28.57
Ground-water gley soils	4153	859	222	75	49.55	33.20	16.16
Man-made soils	238	167	66	55	1.42	0.03	0.00
Peat soils	650	3927	4733	5025	20.65	49.79	33.06
Other land use							
Lithomorphic soils	1904	574	80	85	26.47	0.89	0.21
Pelosols	574	326	66	31	5.55	3.40	1.25
Brown soils	8795	334	71	27	79.85	37.90	6.93
Podzolic soils	5015	1178	93	27	93.01	26.72	4.00
Surface-water gley soils	8729	1978	151	50	134.98	70.83	18.91
Ground-water gley soils	1963	1080	158	51	28.22	12.61	5.13
Man-made soils	197	139	64	55	0.96	0.01	0.00
Peat soils	3241	4046	4815	5057	99.68	257.79	188.26

Table 3. Estimate of the C stock in the upper 150 cm of soils in England and Wales by land use.

Land use	Total organic C stock (Tg)			
	0-30 cm	30-100 cm	100-150 cm	0-150 cm
Arable	367.3	247.0	101.2	715.6
Permanent managed grassland	567.9	322.3	106.6	996.7
Other land uses	470.8	411.0	225.3	1107.1
All land uses	1406.0	980.3	433.1	2819.4

The findings from the LandIS database are discussed in further detail in the evaluation section later in the report, together with the evidence from the literature outlined below. The evidence for the current status of subsoil C in England and Wales from the literature is summarised in Figure 1, based on Appendix 1, and is described below by land use.

Arable soils

The work of Poulton et al. (2003) and Richards & Webster (1999) gave C contents down the soil profile for some of the arable treatments in the Broadbalk experiment (Hertfordshire)[2]. Unfertilised soil had a C content in the 0-23 cm layer of 0.9%, which rose to 1.2% and 3.0% in soil receiving fertiliser and farmyard manure (FYM), respectively. Richards & Webster (1999) found that the long-term FYM treatment still had an effect on C contents at depths of 60-80 cm (up to 0.16% greater), but not at depths below 120 cm where C contents were 0.2-0.3% and differences

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[2] Broadbalk is probably the most well-characterised arable site in England and Wales and, as such, is used here as a benchmark against which to compare other arable soils.

between treatments were not apparent. Surface treatments generally become less apparent with increased depth. Arable soils at geographically-similar locations (Oxfordshire and Berkshire) had C contents at 30-60 cm depth of 1.2-1.3% (Carroll & Oliver 2005), which was greater than the topsoil layers at Broadbalk, with the exception of the FYM-treated soil.
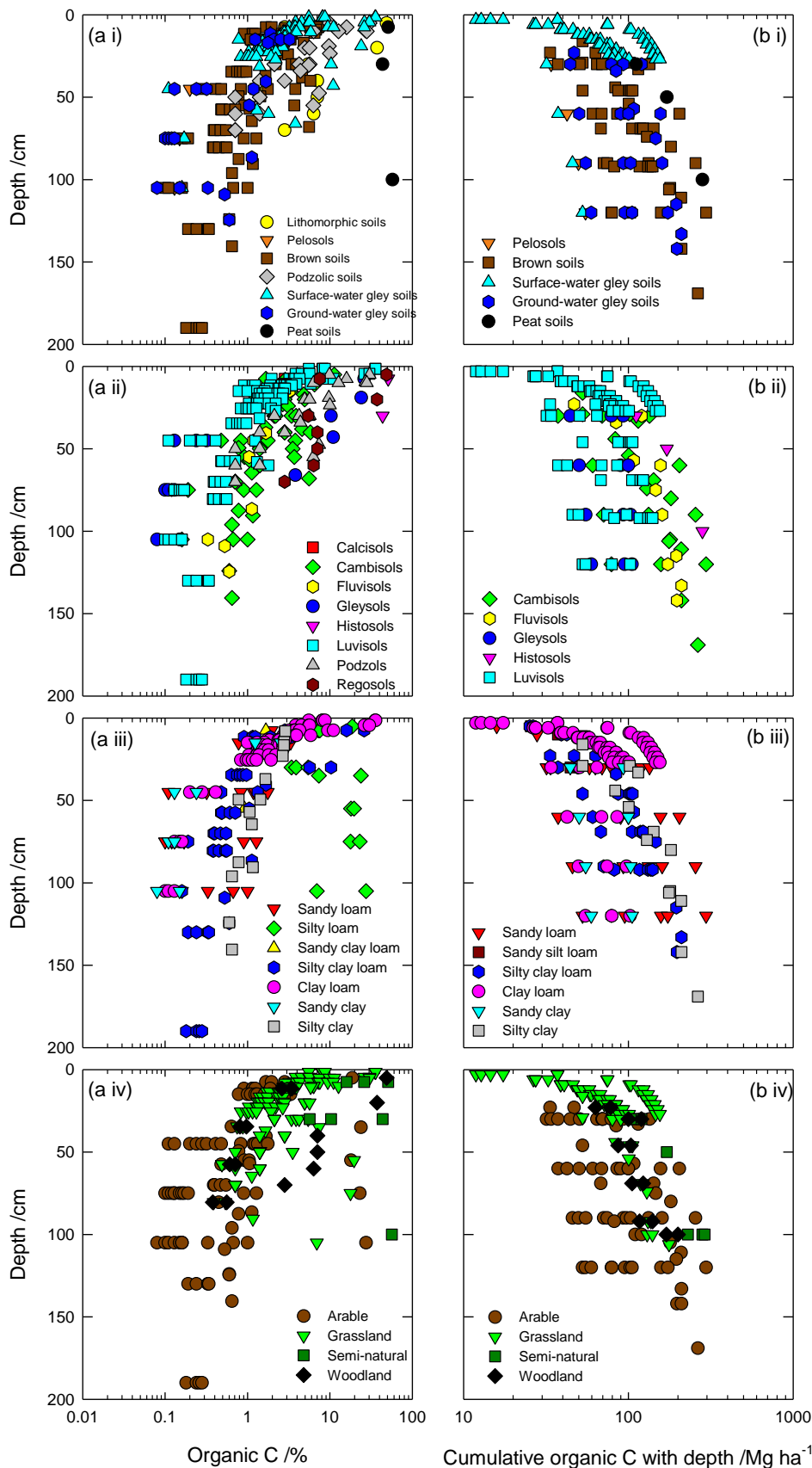

Figure 1. Evidence of the current status of subsoil C in England and Wales. Organic C is shown in units of (a) gravimetric content, and (b) cumulative stock with depth, and the soils are classified by (i) SSEW soil type, (ii) FAO soil type, (iii) texture class, and (iv) land use.

Ellis & Atherton (2003) described C distribution in soils reclaimed from alluvial deposits at Sunk Island in the Humber Estuary (E. Yorkshire). The upper 30 cm had C contents of 1.8-2.8%, which was greater than the arable soil at Broadbalk (except that receiving FYM) but similar to the arable soils studied by Carroll & Oliver (2005). Below 30 cm, the C content was 0.5-1.7%, and total stocks of C in the subsoil layers were much greater than those in the topsoil. A textural effect was found, with silty clay soils having greater C contents than silty clay loam soils, and there was evidence of a chronosequence of C accumulation since reclamation, although this was limited to topsoil C (Ellis & Atherton 2003). Stocks of C on an areal basis were much greater in the alluvial soils than the Broadbalk soil, although it was difficult to compare due to differences in sampling depths.

A similar intensive study was made in floodplain soils of the Trent valley (Nottinghamshire) by Tye (2010). Subsoil C in the 60-120 cm layers was generally 0.1-0.2% except for soils developed on alluvial sands where C contents were 0.7-1.3%. Whereas the floodplain soils had C predominantly found in the upper 30 cm, the alluvial soils had C throughout the profile, including particularly great C contents (1.2-3.3%) and stocks (up to 134 Mg ha^{-1}) in the 0-30 cm layer (Tye et al. 2010).

In their interpolation survey in England and Wales, Bradley et al. (2005) estimated that there is 40-50 Mg C ha^{-1} in the 30-100 cm depth of soil, which is consistent with what has been reported for Broadbalk, but less than that reported for the reclaimed soils at Sunk Island detailed above. Elsewhere, an arable peat soil managed for wetland conservation (S. Yorkshire) was found to have C contents between 18-27% at depths down to 110 cm (Douterelo et al. 2010). The high water table enabled the accumulation of OM, as evidenced by lower C contents in a nearby grassland soil with a lower water table (up to 19% C) (Douterelo et al. 2010).

In addition to the above, Rothamsted and Drayton (Warwickshire) are predominantly arable sites in the UK Environmental Change Network (ECN) where soil samples have been collected on both five- and 20-yearly cycles since 1993. The 20-year sampling (next due in 2013) includes bulk density measurements needed to calculate a stock. The ECN are currently in the process of bringing the database fully up to date, and so information on the current state of subsoil C from their sites should be published in the near-future (ECN, personal communication). A further source is the paper by Adams & Kassim (1984) on soils in mid Wales which gave C contents to depths of up to 84 cm, but unfortunately specific location and land use information was absent. We may speculate that some of the brown soils where the C content did not change significantly with depth in their study were under arable management whereas some of the podzolic and surface-water gley soils with a clearer decline in C content with depth were under grassland, semi-natural or woodland vegetation.

Grassland soils

The two most important benchmark sites in England and Wales that have been under known long-term grassland management are Park Grass at Rothamsted and Palace Leas (Northumberland), and these are used in this review as a benchmark to compare other data to. In addition, North Wyke Research (Devon) is a grassland site in the ECN and there may be data forthcoming on subsoil C contents from recent samplings (ECN, personal communication).

Jenkinson et al. (2008) found that the unfertilised soil had a greater C content (0.5-3.3%) than the fertilised soil (0.4-2.8%) at all depths at Park Grass. The upper 23 cm contained about three times as much C as the 23-46 cm depth in both treatments. Hopkins et al. (2009) reported C contents at Palace Leas down to 27 cm depth in 3-cm depth intervals. This approach is very useful as it gives a fine depth resolution in the topsoil and into the upper part of the subsoil (15-27 cm) with which to study the gradation of C in such uncultivated soils. It was predominantly in the upper 15 cm that differences in soil C were apparent between different manure and fertiliser treatments. There was little difference between control grassland, FYM and phosphorus (P)-fertilised soil (if anything, P appeared to suppress C content slightly), but the grassland receiving nitrogen (N) fertilisation had a considerably greater C content, particularly near the surface where an organic-rich layer had developed. This ranged from 1.7% or 7 Mg ha^{-1} in the 12-15 cm depth to 35.8% or 37 Mg ha^{-1} in the upper 0-3 cm depth. This would suggest an intimate link between soil C and surface vegetation (Hopkins et al. 2009). To compare with the data in Jenkinson et al. (2008), the data of Hopkins et al. (2009) for unfertilised grassland equates to a mean C content of 3.7% (82 Mg ha^{-1}) in the 0-24 cm layer which shows there to be more C stored in the Palace Leas soil than the Park Grass soil. With N-fertilisation, the C stocks increased to a considerable 150 Mg C ha^{-1} for the 0-24 cm layer as a whole. In the subsoil (15-27 cm), Palace Leas had 1.2-2.4 % C (21-37 Mg C ha^{-1}), with a greater amount found in the FYM soil (Hopkins et al. 2009). This was greater than the subsoils of Park Grass. Differences between the Palace Leas and Park Grass soils might in part be due to differences in the predominant climate between northeast and southeast England respectively. The greater rainfall and lower average temperature in northeast England may reduce decomposition rates. In addition, the soil type differs from a brown soil at Rothamsted to a surface-water gley soil at Palace Leas.

Kemmitt et al. (2008) measured the gradation of C down the profile in grassland soils in north Wales, from up to 4.9% at 20 cm to 0.7% at 70 cm depth. Similar contents were reported by Rieuwerts et al. (2006), also in north Wales. The C content from these sites (where it is likely to be relatively wet and cool) was greater than that at Park Grass and Palace Leas. Wet grassland soils at Sunk Island and Sutton Common (S. Yorkshire) had C contents of 2.9 and 7.4%

in the topsoil and at least 1% and 7% down to 106 and 110 cm depth, respectively (Ellis & Atherton 2003; Douterelo et al. 2010).

For the whole of England and Wales, Bradley et al. (2005) estimated that there is 80-90 and 50 Mg ha^{-1} of C in the 0-30 and 30-100 cm layers in grassland soils, respectively, which broadly matches the measurements made at the benchmark Park Grass (both depths) and Palace Leas (just the topsoil, except for N-fertilised soil) sites.

Semi-natural soils

Bradley et al. (2005) have estimated that there is up to 120 and 170 Mg ha^{-1} in the 0-30 and 30-100 cm layers, respectively, in all soils in England and Wales under semi-natural vegetation, representing a considerable stock. This is within the range that others have found in peat soils in northern England (Garnett et al. 2001; Rawlins et al. 2009). Peat soils are particularly important as they can contain more than 200 times the amount of C that is found in the vegetation growing in them (Garnett et al. 2001), and the C contents can be up to 50% (Rieuwerts et al. 2006), even down to 200 cm depth (Rawlins et al. 2009). Podzolic and surface-water gley soils under moorland in Wales had considerably greater C contents than nearby brown soils under grassland (Rieuwerts et al. 2006). Moor House-Upper Teesdale (Cumbria and Co. Durham), Porton Down (Dorset) and Yr Wyddfa-Snowdon (Gwynedd) are semi-natural sites in the ECN and subsoil C data may soon be available (ECN, personal communication).

Woodland soils

Data on C contents in ancient and comparable plantations at three sites in southern England were presented by Wilson et al. (1997). Soils under ancient woodland had more C in the 25-30 cm layer (up to 10.4 Mg ha^{-1}) than the more recent 100-year old plantation woods (up to 6.6 Mg ha^{-1}). In the "wilderness" soils at Rothamsted, where soils were taken out of cultivation in the 1880s and which now support oak, ash, sycamore and hawthorn woodland, C has accumulated when compared with arable soils at the same site (Poulton et al. 2003). Contents in these wooded soils are now are very similar to the long-term grassland soil at Park Grass. By contrast, Kemmitt et al. (2008) recorded much greater C contents in woodland soils than nearby grassland soils in north Wales. At Rothamsted there was more C in the Broadbalk woodland (wilderness) soil than the Geescroft woodland (wilderness) soil. This may reflect soil conditions as the former site still maintains a neutral pH from previous lime applications, whereas the latter site has become strongly acidic (Poulton et al. 2003). Bradley et al. (2005) estimated that the woodland soils of England and Wales contain up to 120 and 80 Mg ha^{-1} in the 0-30 and 30-100 cm layers, respectively. These estimates are greater than the contents measured at Rothamsted. Differences in sampling depths mean that it is difficult to compare this estimate with the ancient woodland sites in the study by Wilson et al. (1997). Additional information on C contents in woodland soils will be available from the Alice Holt (Hampshire) and Wytham (Oxfordshire) ECN sites (ECN, personal communication).

Evidence of the current status of subsoil C in global soils comparable to those in England and Wales

The evidence of the current status of subsoil C in global soils comparable to those in England and Wales (Figure 1; Appendix 1) is summarised in Figure 2 based on Appendix 2.

Arable soils

Tillage experiments in Scotland showed that although different practices could affect surface C contents, the total C stock as a whole in the profile can remain unaffected, although the experiments had only been initiated recently (Vinten et al. 2002; Sun et al. 2011). Gains at the surface with minimum or zero tillage were off-set by losses at depth, compared with conventional tillage. Subsoil C ranged from 1.2-2.7% in the 20-60 cm depth (95-100 Mg ha^{-1} for 20-60 cm) (Sun et al. 2011) which was much greater than those in Broadbalk, presumably due to climatic effects.

Patterns of low C contents in topsoils of around 1% declining to around 0.5% in the subsoil have been reported for arable soils in France (Leguédois et al. 2004; Salomé et al. 2010), Belgium (Lettens et al. 2007) and Germany (Helfrich et al. 2007; Kuka et al. 2007). Don et al. (2009) found a more abrupt decline in C stocks with depth in a sand soil compared with a loam soil in Germany. Stocks in the 0-10 cm depth were very similar to those reported by Sun et al. (2011) in Scotland, but were much lower in the subsoil layers. Kuka et al. (2007) presented data from two long-term arable soils in Germany and the Czech Republic. Stocks in the subsoil (30-200 cm) ranged from 55-69 Mg ha^{-1}, representing a significant stock at depth. Topsoil C stocks were greater than those on Broadbalk too, although one of the soils was a Chernozem which classically has a deep organic-rich top horizon. Sampling to 2 m depth suggests that the soils described by Kuka et al. (2007) were very deep above the parent material.

Helfrich et al. (2007) reported that soil under maize had a slightly greater C content (1.30 and 0.68%) than soil under wheat (1.20 and 0.45%) at 0-30 and 30-45 cm depths respectively, presumably due to different rooting characteristics.

Values of C content and stock in the upper 20 cm of an arable soil in New Zealand have been measured to be 2.9% (Haynes 1999), which is similar to the soils in Scotland reported by Sun et al. (2011). New Zealand has a similar maritime cool temperate climate as the UK.
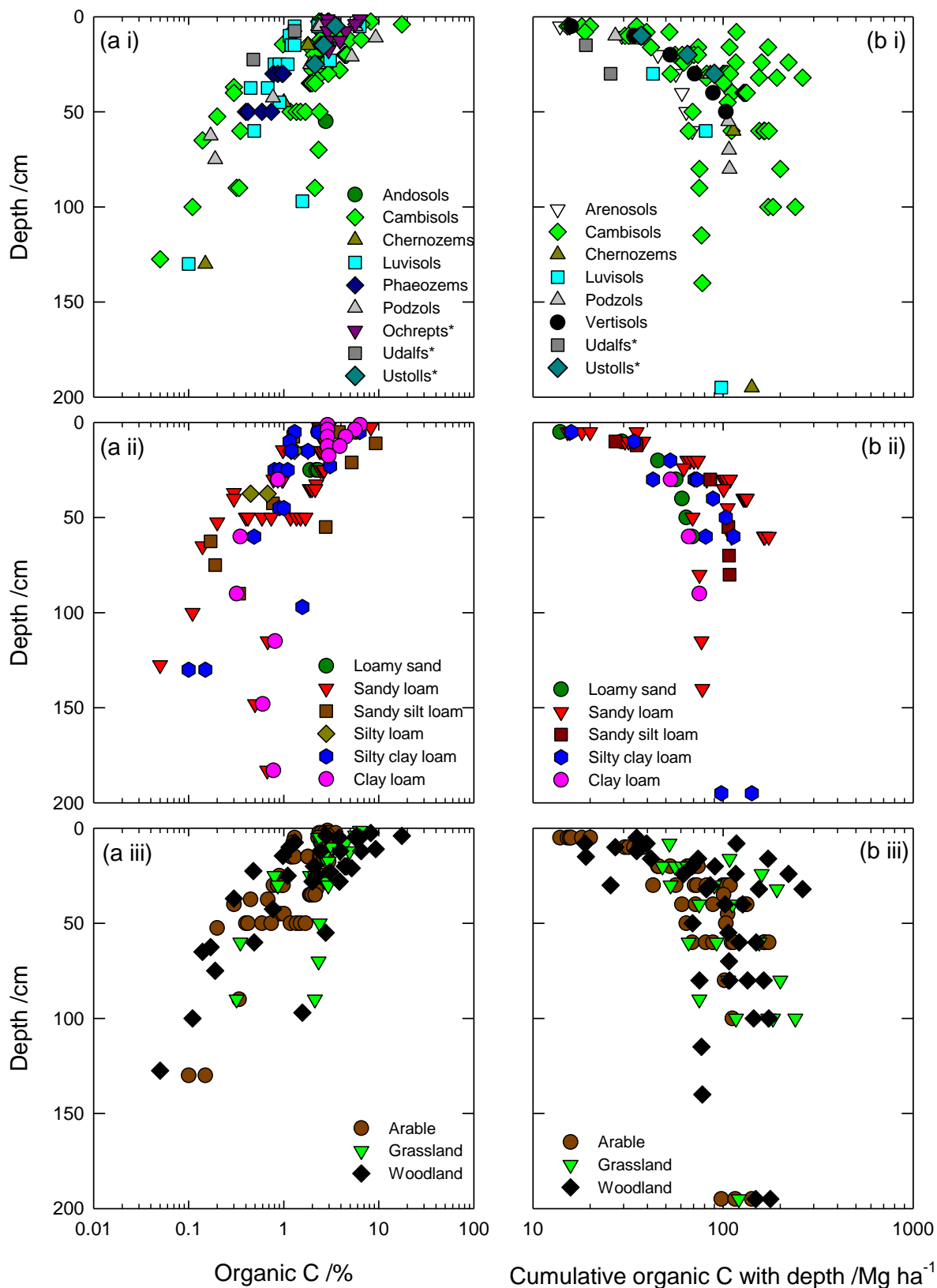

Figure 2. Evidence of the current status of subsoil C in global soils comparable to those in England and Wales. Organic C is shown in units of (a) gravimetric content, and (b) cumulative stock with depth, and the soils are classified by (i) FAO (or USDA*) soil type, (ii) texture class, and (iii) land use.

Jobbágy & Jackson (2000) reviewed the vertical distribution of C down to 3 m in over 2700 soil profiles from three global databases, mainly based on North America, from which data for four biomes (1271 soil profiles under crops, grassland, and deciduous and evergreen forest in temperate climates) have relevance for soils in England and Wales. Estimates of C stocks in arable soil were broadly similar to those measured at Broadbalk, and in addition they estimated there to be 3.8 and 2.7 Mg ha^{-1} in the 1-2 and 2-3 m layers in arable soils. Interestingly, Jobbágy & Jackson (2000) suggest that C at depths of 1-2 and 2-3 m could in part be influenced by surface vegetation, although this might not be the case in England and Wales where many soils are young (post-glacial) and shallow compared with soils on older landscapes in North America from where the database was derived. The correlation with climate decreased for subsoil layers compared to the topsoil (e.g. accumulation of C in the surface of wet soils), when the influence of soil texture becomes more important (e.g. increased clay content at depth) (Jobbágy & Jackson 2000). This might suggest that physical properties in the subsoil are an important control of subsoil C contents.

Grassland soils

Fontaine et al. (2007) showed that a long-term grassland soil in central France had relatively consistent C stocks of 40-56 Mg ha^{-1} in 20-cm depths down to 1 m depth, meaning that its subsoil C stocks were up to three times that of Park Grass. Greater contents were found for 8-cm depths in the soil at Langhill (Scotland) by Fang & Moncrieff (2005). A similar pattern of C contents with depth in the upper 20 cm as that reported by Hopkins et al. (2009) for unfertilised plots at Palace Leas in England was reported by Haynes (1999) in a permanent grassland soil in New Zealand (3-6% C) and by Wang et al. (2009) in a grassland soil in China (2.1-3.5%). Wang et al. (2009) reported a C content of 2.1% in the 20-30 cm depth whereas Haynes (1999) reported a 3.0% C content, but in just the upper part of the subsoil (15-20 cm depth). In long-term grassland soils in New Zealand, Schipper et al. (2007) reported huge C stocks of 96-470 Mg ha^{-1} in subsoil depths ranging from 77-128 cm in a range of 31 soils, with no significant trend between soil types. It was difficult to ascertain the precise thickness of the depths that such C is stored in their paper. Carbon contents of less than 1% were measured in grassland subsoils in France (Sanaullah et al. 2011) and Belgium (Lettens et al. 2007). In the Belgian soil, there was little difference in the subsoil C content between an arable soil and a grassland soil (Lettens et al. 2007). Ammann et al. (2009) found that managing a grassland soil in Switzerland intensively increased the C content in both the 0-20 cm and 20-100 cm depths.

In their study of data from three global databases, Jobbágy & Jackson (2000) estimated that stocks for temperate grassland range from 48 Mg ha^{-1} in the 0-20 cm layer to 10 Mg ha^{-1} in the 80-100 cm layer, with 4 and 3 Mg ha^{-1} stored in the 1-2 and 2-3 m layers, respectively. The relative distribution of C (if not the absolute) was deeper for grassland than woodland, representing different vegetation influences (Jobbágy & Jackson 2000). With the exception of a greater stock in the topsoil, the Park Grass soil broadly matched this global average. It is possible that Park Grass is managed more intensively than most temperate grassland. Sourhope (Borders, Scotland) and, in particular, Hillsborough (Co. Down, N. Ireland) are ECN sites in the UK under grassland management and there may be unpublished data on subsoil C contents from recent samplings (ECN, personal communication).

Semi-natural soils

There was no published data available for soils under semi-natural vegetation. However, Glensaugh (Aberdeenshire, Scotland) and Cairngorms (Highland, Scotland) are ECN sites largely under semi-natural vegetation comparable to England and Wales (i.e. not under arable, grass or woodland) and there will soon be data on subsoil C contents from recent samplings (ECN, personal communication).

Woodland soils

Stocks for deciduous woodland in the review of Jobbágy & Jackson (2000) were greater than those recorded for Broadbalk and Geescroft wilderness (Poulton et al. 2003) and the ancient woodland in England (Wilson et al. 1997). The woodland on the wilderness soils are undoubtedly of a much younger age than the deciduous woodland soils reported in the databases. Jobbágy & Jackson (2000) also reported stocks for temperate evergreen woodland soils (145 Mg ha^{-1} in the top 1 m), which may be analogous to coniferous woodland soils in England and Wales, either naturally in the uplands or as plantations. Jobbágy & Jackson (2000) suggest that such soils have a slightly lower C stock throughout their profile compared to deciduous woodland soils, which may reflect shallower rooting of coniferous trees.

The data of Eusterhues et al. (2003) and Kögel-Knabner et al. (2008) for temperate (European beech and European oak) and coniferous (Norway spruce) woodland soils in Germany had C stocks much lower than that in the database of Jobbágy & Jackson (2000), being less than 1% below 30 cm. Eusterhues et al. (2003) and Kögel-Knabner et al. (2008) concluded that a greater proportion of C is stabilised in association with minerals at depth in the sandy soils in their study, and that there was more C in soils under deciduous species than coniferous species. Carbon contents of up to 2.8% in the subsoil of both deciduous and coniferous forest soils in Germany have also been reported (Siregar et al. 2005; Kleber et al. 2005). Lettens et al. (2007) found less C in woodland soils than grassland soils in Belgium.

Fang & Moncrieff (2005) reported similar in Scotland, and found greater C contents under Scots pine (262 Mg ha^{-1} in 0-32 cm) than under Sitka spruce and birch (81-164 Mg ha^{-1}).

4. Review of the dynamics of subsoil C in England and Wales

Evidence of the dynamics of subsoil C in England and Wales

Evidence of the dynamics of subsoil C in England and Wales is summarised in Figure 3 based on Appendix 3.

Continuous long-term management

There are currently only two sites in England and Wales with published data on subsoil C dynamics, namely Rothamsted (Poulton et al. 2003; Jenkinson et al. 2008) and Palace Leas (Hopkins et al. 2009). Future data on C dynamics in subsoils with a known history will derive from the eight ECN sites in England and Wales.

Under long-term arable for centuries, there was an initial large increase in C in the 0-69 cm depths of 100 to 200 kg C ha^{-1} yr^{-1} (per 23-cm depth) since 1893, followed by a more modest increase of up to 24 kg C ha^{-1} yr^{-1} since 1904 in Broadbalk (Poulton et al. 2003). The 69-92 cm depth has increased its C stock since 1904. Poulton et al. (2003) also reported a loss of carbonate C which had derived from the previous liming treatments that were historically applied on Broadbalk. Following a small loss of C from 1870 to 1876 in fertilised grassland, and to 1906 in unfertilised grassland, there have been accumulations of C since 1906 at all depths generally in the grassland plots at Park Grass (Jenkinson et al. 2008). This has ranged from 29 to 83 kg C ha^{-1} yr^{-1} (per 23-cm depth) in the subsoil depths (those deeper than 23 cm).

Hopkins et al. (2009) reported the change in soil C between 1982 and 2006 in six grassland treatments at the Palace Leas site in northeast England. Four of the treatments showed an increase in soil C taking the 0-27 cm depth layer as a whole ranging from 250 to 930 kg C ha^{-1} yr^{-1}. Two treatments – the control and the P-fertilised grassland – showed a decrease of 140 and 310 kg C ha^{-1} yr^{-1} respectively. Specifically for the subsoil (15-27 cm), changes in C ranged from a decrease of 214 kg C ha^{-1} yr^{-1} to an increase of 318 kg C ha^{-1} yr^{-1}. Hopkins et al. (2009) pointed out that C decreases were in the same order of magnitude as the changes in bulk density (from which stocks are derived), which were dependent on water content, and that overall there were few significant changes in C with time.

Taking Rothamsted and Palace Leas together, there is little evidence that there has been a significant loss of soil C while air temperatures have been increasing, and indeed the evidence suggests that under stable long-term management the Rothamsted soils have accumulated C. The most likely explanations are that subsoil C is largely stable and that inputs from increased plant growth have negated any increased loss of C through increased microbial activity (Hopkins et al. 2009). In addition, any loss of C in the topsoil at the two sites (which has been found in some treatments) appears to have been balanced or negated by increases in subsoil C.

The reclaimed alluvial soils at Sunk Island described in the study of Ellis & Atherton (2003) represent a chronosequence of soils of different ages and thus can also be used to assess C dynamics. There was evidence that C contents in the topsoil (0-30 cm approximately) increased with soil age from about 1.9% and 47 Mg ha^{-1} for 100-year old soils to 2.8% and greater than 100 Mg ha^{-1} for 200-year old soils. It is difficult to assess the dynamics of C stocks in the subsoil due to the different sampling depths but there was little difference between soils of different ages in terms of C content. For woodland soils Wilson et al. (1997) reported that a 100-year plantation in the New Forest had greater C contents in the topsoil than ancient woodland, but in the 25-30 cm depth C contents were significantly greater in the latter.

Changes in soil management

Poulton et al. (2003) reported that abandoning old arable land on Geescroft and Broadbalk led to an almost linear increase in C of 380 and 540 kg C ha^{-1} yr^{-1} respectively in the upper 69 cm of the soil and the litter over a 118 year period as woodland regenerated, which seems to be continuing to this day. The estimates based on just the soil C data show that Broadbalk accumulated C at a rate of up to 496 and up to 87 kg C ha^{-1} yr^{-1} in the 0-23 cm and 23-46 cm layers respectively, and the comparable figures for Geescroft were 453 and 69 kg C ha^{-1} yr^{-1} respectively. Interestingly, Broadbalk accumulated C at a faster rate in the 1881-1964 period and a slower rate from 1964-1999 compared with Geescroft, at all depths. Poulton et al. (2003) believed that the greater N availability and light interception on the smaller Broadbalk wilderness compared to Geescroft to be responsible for the initial differences in C accumulation.

Also at Broadbalk, slightly more C accumulated where the vegetation was stubbed to grassland. Retention under stubbed management had a greater C accumulation rate in the subsoil (up to 137 kg C ha^{-1} yr^{-1} for 23-46 cm depth) than a grazing treatment (up to 29 kg C ha^{-1} yr^{-1} for 46-69 cm depth) from 1964-1999. In addition, Poulton et al. (2003)

measured above-ground biomass C, root C and litter C, which also increased following regeneration from arable to woodland. This supports the view that soil C is directly proportional to the annual input of plant C (Jenkinson et al. 1992).
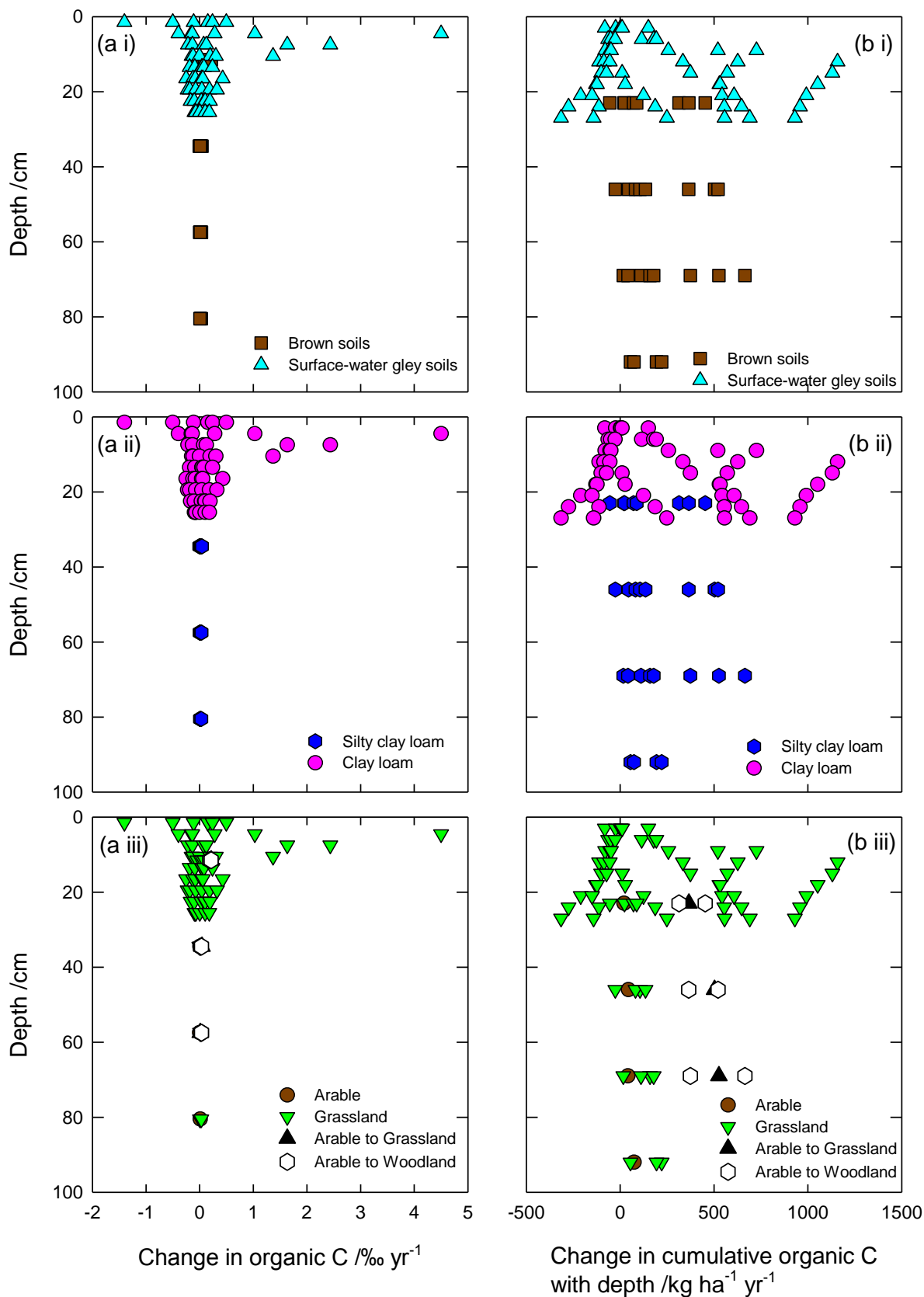

Figure 3. Evidence of the dynamics of subsoil C in England and Wales. The change in organic C is shown in units of (a) gravimetric content, and (b) cumulative stock with depth, and the soils are classified by (i) SSEW soil type, (ii) texture class, and (iii) land use or change in land use.

Adding lime to grassland soil resulted in a greater C accumulation rate in the top 0-23 cm (88 kg C ha^{-1} yr^{-1}) but a lower accumulation rate at 23-96 cm depths (up to 47 kg C ha^{-1} yr^{-1} for the 23-46 cm depth) when compared to unlimed grassland at Park Grass reported earlier (Jenkinson et al. 2008).

Evidence of the dynamics of subsoil C in global soils comparable to those in England and Wales

Evidence of the dynamics of subsoil C in global soils comparable to those in England and Wales (Figure 3; Appendix 3) is summarised in Figure 4 based on Appendix 4.

Continuous long-term management

Schipper et al. (2007) reported very large losses in the C content of the subsoil layers, from 77 to 130 cm depth, of a range of pasture soils in New Zealand from 1976 to 2005. Of the 31 soils re-sampled, 22 soils had lost C at a rate of up to 8.8 Mg ha^{-1} yr^{-1} (in a 10-cm layer). The mean for all soils was a loss of 1.1 Mg ha^{-1} yr^{-1}. They believed that losses through leaching and erosion would only account for a fraction of this loss, and hence their report does suggest that C has been lost from grassland soils down to 130 cm depth. One suggestion is that these soils are still adjusting from the time that the forests were cleared for agriculture (from the 1840s onwards) (Schipper et al. 2007), which is a view that has been expressed elsewhere (Smith et al. 2007).

Changes in soil management

Don et al. (2009) reported that conversion of arable soils to grassland soils resulted in an increase in the C stock in the upper 10 cm (gains of 50-900 kg ha^{-1} yr^{-1}) but a decrease in the 10-50 cm depth (losses of 150-740 kg ha^{-1} yr^{-1}) in a study in Germany. They believed that decreases in bulk density off-set the increase in C contents following conversion, and that a considerable amount of C was stabilised on minerals in arable subsoils. Using radiocarbon data, they found that there could be a rapid transfer of C to the subsoil, partly aided by ploughing of arable soils (Don et al. 2009). Related to this, Vinten et al. (2002) advised that where a grass ley has to be cultivated to arable, deep ploughing was preferable to minimum tillage in order to put C and nutrients lower in the profile where they are more likely to be stabilised.

Haynes (1999) reported increases in C of up to 3.6 ‰ yr^{-1} in the upper 15 cm in the first five years following conversion of an arable soil in New Zealand to grassland, but no change in the 15-20 cm depth. Continuous grassland accumulated C quicker than annually-tilled soil, suggesting that it is important to exclude cultivation if changing to pasture is to maximise C sequestration, although this was restricted to the 0-15 cm depth rather than the 15-20 cm subsoil depth reported. Also, Haynes (1999) found that the microbial biomass C increased rapidly upon conversion to grassland such that it comprised a similar fraction of total C as long-term pasture. Wang et al. (2009) found that conversion of meadow steppe grassland soils to an arable land use was followed by a loss of up to 340 kg ha^{-1} yr^{-1} in the upper 10 cm and a much smaller loss of up to 69 kg ha^{-1} yr^{-1} in the 20-30 cm layer in China.

5. Evaluation of the current status and dynamics of subsoil C in England and Wales

The current status of subsoil C in England and Wales

The effect of soil type

Some patterns with soil type are apparent from the literature review and the LandIS dataset. Most obviously peat soils (FAO: Histosols) can have C contents exceeding 10% down to 1 m, equating to total stocks of over 7000 Mg ha^{-1}, representing a considerable repository of C. Surface-water gley soils (FAO: Gleysols) have greater C contents at the surface, presumably where decomposition is inhibited in comparison to better-drained soils. This is illustrated by the greater C content of the gley soil at Palace Leas compared to the brown soil at Park Grass, both of which are under long-term grassland management. Podzolic soils can also have more than 1% C in the subsoil. Shallow lithomorphic soils (FAO: Regosols) have C contents of greater than 2% in the subsoil. Particularly low C contents were found in pelosols. Most soils in the review were brown soils (FAO: Luvisols and Cambisols) with a wide range of C contents in the subsoil ranging from less than 0.5% to 5%. Bradley et al. (2005) reported greater subsoil C contents for the upland organic soils in the north and west of England, and in Wales, than mineral soils in the south and east of England. Soils of alluvial origin can also have considerable C contents.

A fundamental property linked to soil type is soil texture. There is some evidence that clay soils have more C than loamy soils, a finding that would be expected to be related to adsorption and surface area, although there was not a great range of texture classes in the review for evaluation. Within soils, there could be significant changes in the texture between horizons due to soil forming processes including downward clay translocation. Such a process may be associated with enrichment of C contents at depth.
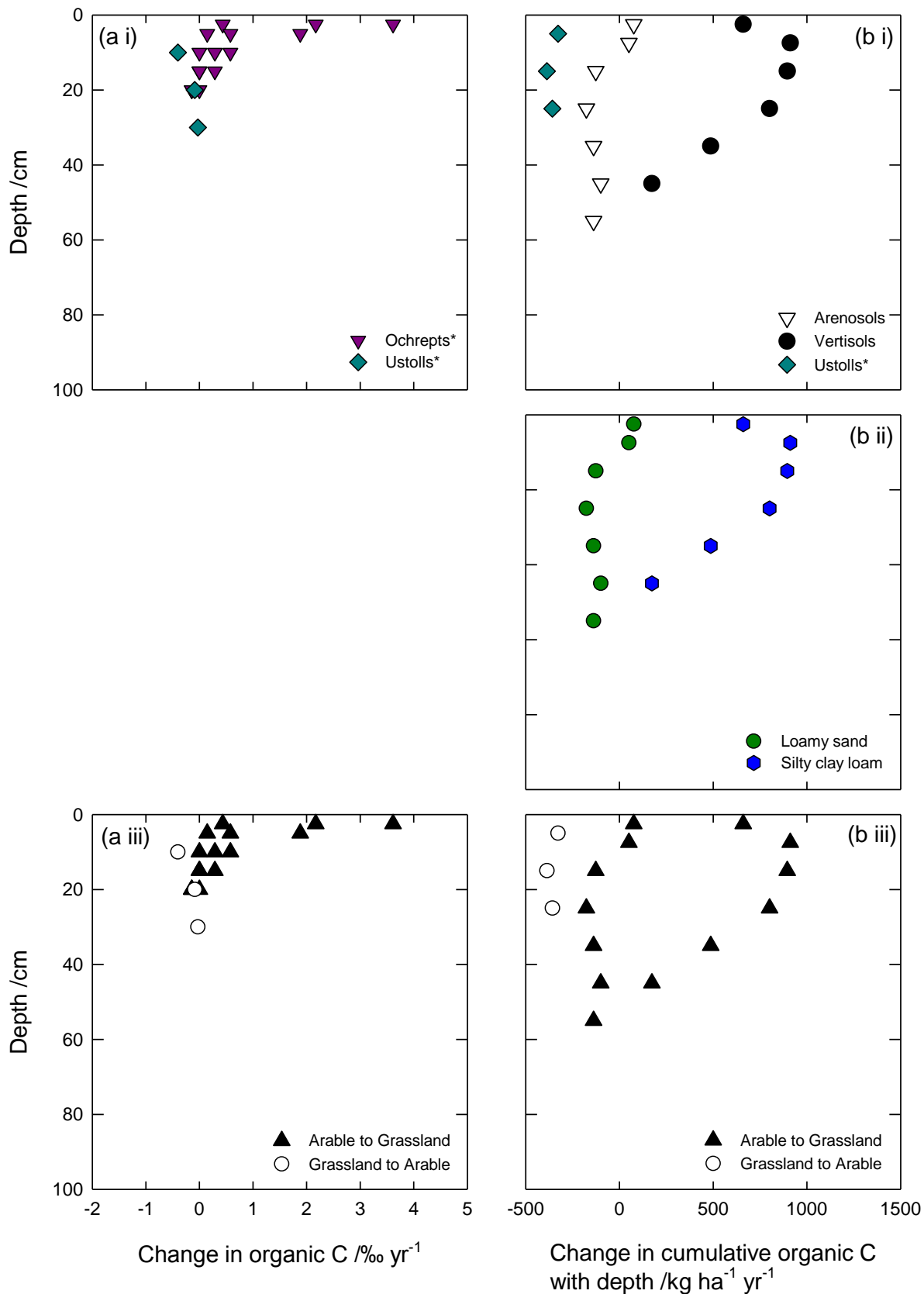
Figure 4. Evidence of the dynamics of subsoil C in global soils comparable to those in England and Wales. The change in organic C is shown in units of (a) gravimetric content, and (b) cumulative stock with depth, and the soils are classified by (i) FAO (or USDA*) soil type, (ii) texture class, and (iii) change in land use.

For all soils in the review taken together, the C content is generally above 0.1% in the subsoil down to 2 m, with an areal content of 50-200 Mg ha^{-1} down to 1 m. Although a definitive threshold C content for soil functioning has not yet been demonstrated, a value of 1% (linked to N supply from OM) has been suggested (Loveland & Webb 2003). Based on this somewhat arbitrary indicator, it would appear that the majority of soils types in England and Wales have greater C contents than this in the topsoil, suggesting that most topsoils are not likely to be in a critical condition

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related to soil functioning currently. That is to say nothing about the current trends in organic C content however. In the subsoil lithomorphic soils, podzolic soils, surface-water gley soils and peat soils have more than 1% C, whereas the pelosols and the ground-water gley soils have less than 1% C. Brown soils are spread across the threshold.

The effect of land use

Under long-term management, soil C reaches an equilibrium content that decreases with depth. Relationships have been established between depth and C content, pointing to a smaller C content at depth that is less-similar to the isotopic content of the surface vegetation and is of great age (Jenkinson et al. 2008). In this respect soil C is directly proportional to the annual input of C from surface vegetation. Bradley et al. (2005) found that arable soils in the south and east of England have lower C contents than soils under grassland or semi-natural vegetation in the north and west of England and Wales, although arable soils were more widespread in their study. In our review, grassland soils often have a C content greater than 1% at 1 m depth, whereas the corresponding figure for arable soils is less than 1%. Grassland and semi-natural soils contain up to 200 Mg ha^{-1} in the upper 1 m compared to less than 100 Mg ha^{-1} in arable soils, although there is a large spread of data. Soils under ancient woodland are likely to be important stores of C (Wilson et al. 1997).

For most soil types in the LandIS database, there is an increase in the areal C stock in the 0-30 cm depth as the land use changes from arable to grassland to other. The increase in our study is particularly great for podzolic and both surface- and ground-water gley soils. It is possible that OM accumulates in wet soils in the absence of cultivation. Man-made soils under arable land use have greater C contents than those under other land uses. For the subsoil depths (30-100 and 100-150 cm), lithomorphic soils, brown soils, surface-water gley soils and peat soils have greater C stocks under grassland and other land uses compared to arable land uses. Semi-natural vegetation often corresponds with organic peat soils. In addition, pelosols and ground-water gley soils follow the same pattern in the 30-100 cm depth but not in the 100-150 cm depth, where there is little difference between land uses for pelosols and greater C contents under arable land uses for ground-water gley soils. Surface land use does not appear to affect C stocks in the subsoil of podzolic soils.

In the literature review of sites where the same soil is under different management regimes, the regimes tend to affect total C in the upper part of the subsoil (to 45 cm), whereas C at greater depths is little-affected by surface vegetation (Poulton et al. 2003; Jenkinson et al. 2008). There was more data on woodland soils from studies outside of England and Wales. With the exception of the topsoil, there is little difference between the C content of arable, grassland and woodland soils; all generally contain 100-200 Mg ha^{-1} in the upper 1 m. An exception to this is the woodland soils at Rothamsted which are linked to a greater C content at 46-92 cm depth than comparable arable and grassland soils, particularly the small area of woodland at Broadbalk wilderness on neutral soils (Poulton et al. 2003). Nevertheless, Jenkinson et al. (2008) reported C contents at depths of 114-137 cm and 206-229 cm in samples collected from an arable plot at Broadbalk in 1893 of 0.24 and 0.20% and 7.6 and 6.7 Mg ha^{-1}, respectively, which might still represent an important sink of C.

Small changes within the same general land use can also affect soil C contents down the profile. Examples include the different rooting patterns of different arable crops (Helfrich et al. 2007), and the use of organic and inorganic fertiliser to increase the productivity of both arable crops (Richards & Webster 1999) and grasses (Hopkins et al. 2009) – both strategies have been associated with increased C contents. Different tillage practices have been found to affect the distribution in the profile rather than the amount of C (Vinten et al. 2002; Sun et al. 2011).

The current dynamics of subsoil C in England and Wales

The effect of land use

A full evaluation of the current dynamics of subsoil C in England and Wales is not possible due to the lack of evidence currently available. The evidence that does exist is restricted to specific sites and to a comparison between land uses. Based on this, there is no evidence of a significant change in soil C contents and stocks below 30 cm under long-term arable or long-term grassland (Poulton et al. 2003; Jenkinson et al. 2008). If anything there has been a slight increase in the areal stock but not the gravimetric content. Converting arable land to grassland or woodland at Rothamsted has caused an increase in the C stock of up to 0.5 Mg ha^{-1} yr^{-1} from the surface to 79 cm depth (Poulton et al. 2003). The main changes in soil C under both long-term and changing land use have been felt in the topsoil and these have largely been increases rather than decreases. At Palace Leas this has been over a period from 1982 to 2006 (Hopkins et al. 2009), whereas the changes at Rothamsted represent the period from the early 1900s to 1999 (Poulton et al. 2003; Jenkinson et al. 2008).

There is some contrasting evidence from outside of England and Wales. Don et al. (2009) reported increases in topsoil C but decreases in subsoil C 20 years following conversion from arable to grassland in a soil in Germany, whereas Haynes (1999) reported large increases at most depths following a similar conversion in New Zealand.

Therefore, with the exception of where grassland soils (and presumably semi-natural and woodland soils) are converted to arable land uses, subsoil C contents appear to be either at equilibrium under long-term management or are increasing slightly. In agricultural soils, it might be the case that intensification has been matched with increases in the supply or stabilisation of C in the subsoil. It does need to be reiterated, however, that there is very little evidence on the actual current dynamics of subsoil C in England and Wales and that it is likely that soils take a considerable time to equilibrate to changing conditions (Schipper et al. 2007; Smith et al. 2007).

Predictions of the effect of expected changes in climate

There has been considerable interest in the likely impacts of climate change of soil C in general and whether a negative (increased net primary productivity, increased soil C, less C returned to the atmosphere) or a positive feedback (increased C decomposition, decreased soil C, more C returned to the atmosphere) will result.

The study by Bellamy et al. (2005) reported a mean relative (to the initial C content) loss of C in the 0-15 cm depth of soils in England and Wales of 0.6% yr^{-1} (0.6 ‰ yr^{-1} in absolute terms) and up to 2% yr^{-1} (7 ‰ yr^{-1} in absolute terms) in organic soils over the period 1978-2003. They suggested climate change as being responsible based on the lack of significant effects of soil type and land use. Movement to depths below 15 cm was suggested as a possible explanation for some of the loss. Losses of topsoil C in France have also recently been partly attributed to increased temperature (Saby et al. 2008). Emmett et al. (2010) reported no net significant change in topsoil (0–15 cm) C in the whole of Britain between 1978 and 2007, although this partly masked a significant increase from 1978 to 1998 and a significant decrease from 1998 to 2007, and also a significant loss in arable soils. Climate change was ruled out as having a significant effect on topsoil C. Smith et al. (2007) also dismissed climate change as being the main factor in the Bellamy et al. (2005) study and suggested that unreported changes in land use, agricultural management, and bulk density were more-likely factors behind the apparent loss, although again there was no mention of the subsoil. King et al. (2005) modelled the trend in topsoil C contents in arable soils in England over the period 1940-2000, and ascribed the general decline in contents largely to a decline in the area of permanent and temporary grassland since the Second World War. Similar conclusions on the precedence of changes in land use and soil management over changes in climate have been reported for soils in Belgium (Goidts & van Wesemael 2007; Stevens & van Wesemael 2008). Hopkins et al. (2009) found that long-term grassland that had been subjected to recent rises in atmospheric CO_2 did not lose C from the topsoil. More recent modelling work by Kirk & Bellamy (2010) has led them to agree that land use changes are probably key and that, given the magnitude and scale of such effects, it will be difficult to detect climate-change-induced changes in soil C until they are already well advanced and of a comparable magnitude to the management-induced changes.

All of the above debate is concerned with effects in the topsoil however. At Rothamsted over the past 100 years, losses in topsoil C which have occasionally been recorded appeared to have been balanced or negated by increases in subsoil C (Poulton et al. 2003; Jenkinson et al. 2008), although it would be difficult to extrapolate these historical findings with the more recent changes in climate. A review by Davidson et al. (2006), largely concerned with temperature effects, did not distinguish between different depths in the soil. There appears to be a consensus view that labile forms of C are subjected to a temperature-sensitive increase in decomposition with rises in temperature. The complication is then that much soil C is "stabilised" in some form, and the effects of climate change can only be speculated on. For instance, Davidson et al. (2006) described some possible effects that changes in climate would have, including changes in soil aggregation (e.g. release of C from eroded soil), reaction thermodynamics (e.g. adsorption of C), soil hydrology (e.g. diffusion rates, water films, hydrophobicity), and soil microclimate (e.g. increased depth of biological activity).

The greater temperature sensitivity to decomposition of more recalcitrant C was recently demonstrated for soils from a wide range of climatic regions by Craine et al. (2010) based on soil microcosm measurements and the Arrhenius equation. They showed that where soils have lower rates of respiration at a reference temperature of 20 °C (i.e. more recalcitrant OM) the greater its sensitivity to temperature increases. Subsoils generally contain a greater proportion of recalcitrant OM than topsoil so we might expect there to be greater relative losses of C from the former compared to the latter with rising temperatures predicted from climate models.

Experimental data on the effect of aspects of climate change on soil C is available in the literature. Hagedorn et al. (2001) described an experiment where sandy loam and loamy sand spruce-beech model ecosystems in Switzerland were subjected to an enhanced CO_2 atmosphere (570 ppm) for four years. After four years, soil C in the 0-10 cm depth was greater by 5–8% (up to 1.8 Mg ha^{-1}) in the CO_2-enhanced atmosphere, when compared to soil subjected to ambient conditions (370 ppm CO_2), but C contents at greater depths were not affected. Schlesinger & Lichter (2001) reported much the same in pine forest soils in the USA under an elevated 565 ppm CO_2 atmosphere whereby C in the upper 15 cm increased significantly by 20% in three years (0.933 ‰ yr^{-1}; 1021 kg ha^{-1} yr^{-1}), but C contents in the 15-30 cm depth, though increased by 0.183 ‰ yr^{-1}, were not significantly affected. In both studies, the isotopic signature of the atmospheric CO_2 was felt at depths down to 30 cm (Schlensinger & Lichter 2001) and 50 cm (Hagedorn et al. 2001), indicating incorporation of new C at depth. In the acidic loam the net input of new C in the whole profile (0–100 cm) was 6.7 Mg ha^{-1}, which was greater than the calcareous sand, which was ascribed to slower decomposition in the

former soil (Hagedorn et al. 2001). It was believed that elevated CO_2 stimulated root growth (Hagedorn et al. 2001). It should be noted that the current annual rise in atmospheric CO_2 is approximately 2 ppm (Keeling et al. 1995) and so the work is simulating a situation in many decades time, assuming a linear increase, or sooner if the rate itself is increasing exponentially (Hofmann et al. 2009). Van Groenigen et al. (2006) examined published data on the effects of enhanced CO_2 on soil C, and concluded that only when there was an addition (or a reduction in loss) of N would soils accumulate C as atmospheric CO_2 increased, although there was no mention of patterns with depth. Schlesinger & Lichter (2001) concluded that there was limited potential for long-term sequestration of C in the soils under the pine forest as CO_2 concentration increased, based on the rapid turnover of fresh C.

Gaps in our knowledge on subsoil C in England and Wales

During the course of this review it has become apparent that there is a wealth of data of C contents down the profiles in soils in England and Wales. Most of this has been collected on an *ad hoc* basis, often for other purposes. Other data has been collected on a more systematic basis either by the original soil profile mapping of the Soil Survey of England and Wales and its successors, or by others on well-established sites (e.g. Rothamsted). As a consequence of the wide range of sources of data, there has been a range of C quantification methods applied largely divided between those based on combustion and those based on chemical reaction. Future monitoring will benefit from the established protocol for monitoring C contents that will arise from sub-project iv of the current project (Wallace et al. 2011).

There is very little data on C contents down the profile into the subsoil as measured over time at the same sites. To our knowledge the only repeated measurements on subsoil C have been infrequent measurements on the long-term field experiments at Rothamsted Research and at Newcastle University's Palace Leas experiment, and the five-yearly measurements at the ECN sites, from which the data is not yet available. Therefore we are only able to offer a very tentative view on the current dynamics of C in the subsoil.

Some C in the subsoil undoubtedly derives from the underlying parent material rather than from surface or root inputs. Further studies are required to establish the quantities of fossil C incorporated into the subsoil from organic-rich parent materials, such as Oxford and Kimmeridge Clays, which form the parent material of soils across considerable parts of England and Wales.

Modelling subsoil C and its dynamics has lagged behind modelling topsoil C and could be improved upon. Jenkinson & Coleman (2008) have devised a new model for organic C turnover in the upper 1 m of the profile (RothPC-1, "profile carbon"). This is based on a modification of the Rothamsted C model (RothC-26.3) with extra parameters that move C down the profile by advection and which decrease the decomposition rate constants with depth, in a series of up to five depths. Helfrich et al. (2010) also reported a change in decomposition coefficients with depth in a C model fitted with data derived from C_3 and C_4 vegetation inputs, but pointed out numerous weaknesses and gaps, including insufficient data on parameters such as bulk density and root distribution, and C isotope contents that were close to the limit of detection. Kuka et al. (2007) developed a model based on the protection of C in a range of pore sizes. A factor based on distance from the soil surface was included which could account for the subsoil.

If improved models of subsoil C are forthcoming, however, then this could potentially improve our understanding of the likely effects of climate change on subsoil C. Jenkinson and Coleman (2008) suggest that subsoil C may not decline as quickly as surface soil C a result of changes in atmospheric CO_2, but may be stabilised or may even increase if the response of the surface vegetation is positive. Studies at Rothamsted have suggested that subsoil C can be affected by dramatic changes in soil management (Poulton et al. 2003), and so if climate change does affect surface vegetation then some change in the subsoil might be expected.

6. Summary

- It is estimated that there is 980 Tg of organic C in the 30-100 cm depth of soils in England and Wales, representing a considerable store of C.
- Subsoil C is largely dependent on the soil type, with peat soils having particularly great C contents.
- Although land use largely affects topsoil C content, it has also been found to have an effect on subsoil C contents: at 1 m depth soils under grassland generally have C contents greater than 1% whereas those under arable generally have less than 1% C.
- Total subsoil C contents probably change very slowly over time when a change occurs, such as a change in land use, although there is some evidence from isotope studies that a quicker response can be found in certain C compounds.
- There is very little evidence from which to assess the current dynamics of subsoil C in England and Wales, but what evidence we do have suggests that subsoil C contents under long-term arable or long-term grassland are stable.
- How changes in climate will affect subsoil C remains unknown, although some effect might be expected if there is a both a vegetation response to climate change and a definitive link between surface vegetation and subsoil C.

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- Future assessments of the status and dynamics of subsoil C will benefit from a standardised C quantification method, systematic sampling at benchmark sites (particularly the ECN), and advances in modelling.

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Appendix 1. Evidence of the current status of subsoil C in England and Wales.

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
Broadbalk, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable; wheat	1999 / >350	0-23 23-46 46-69 69-92	1.15 0.64 0.48 0.45	33.5 19.3 15.3 13.9	Combustion	Poulton et al. 2003
Broadbalk, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable; wheat unfertilised	1992 / 149	0-23 60-80 120-140 180-200	0.91 0.47 0.34 0.26	?	Combustion	Richards & Webster 1999
Broadbalk, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable; wheat N-fertilised	1992 / 140	0-23 60-80 120-140 180-200	1.24 0.40 0.19 0.18	?	Combustion	Richards & Webster 1999
Broadbalk, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable; wheat high N-fertilised	1992 / 108	0-23 60-80 120-140 180-200	1.16 0.39 0.24 0.28	?	Combustion	Richards & Webster 1999
Broadbalk, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable; wheat FYM-fertilised	1992 / 149	0-23 60-80 120-140 180-200	3.01 0.55 0.33 0.24	?	Combustion	Richards & Webster 1999
Crowmarsh Battle Farms, Oxon.	Rendzina (Calcisol) / silty clay loam	Chalk	Arable	2002 / ?	0-15 30-60	[a] 2.84 1.33	?	Loss-on-ignition	Carroll & Oliver 2005
Yattendon Estate, Berks.	Brown sand (Luvisol) / sandy loam	Reading Beds over chalk	Arable	2001 / ?	0-15 30-60	[a] 1.96 1.24	?	Loss-on-ignition	Carroll & Oliver 2005
Long Close, Wellesbourne, Warks.	Brown earth (Cambisol) / sandy clay loam	?	Arable	2003 / ?	0-15 50-60	[a] 1.67 0.92	?	Combustion	Rodríguez-Cruz et al. 2006
Hatfield Moor, S. Yorks.	? / silt loam	Peat	Arable; wetland conservation	2004 / ?	0-10 30-40 50-60 70-80 100-110	[a] 18.73 23.84 18.00 23.08 27.45	?	?	Douterelo et al. 2010
Whitehouse Farm, Sunk Island, E. Yorks.	Brown calcareous alluvial soil (Cambisol) / silty clay	Alluvium over Quaternary glacial and lacustrine sediment	Arable	2000 / 260	0-29 30-69 70-105 106-142	2.79 0.78 0.78 0.60	101.9 40.5 36.9 30.5	Dichromate titration	Ellis & Atherton 2003

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
Winestead Farm, Sunk Island, E. Yorks.	Brown calcareous alluvial soil (Cambisol) / silty clay	Alluvium over Quaternary glacial and lacustrine sediment	Arable	2000 / 200	0-33 34-80 81-111 112-169	2.76 1.06 0.65 0.65	114.8 66.3 27.9 55.2	Dichromate titration	Ellis & Atherton 2003
Newlands Farm, Sunk Island, E. Yorks.	Alluvial gley soil (Fluvisol) / silty clay loam	Alluvium over Quaternary glacial and lacustrine sediment	Arable	2000 / 150	0-34 35-75 76-142	1.77 1.05 0.53	84.3 62.2 50.7	Dichromate titration	Ellis & Atherton 2003
Outstray Farm, Sunk Island, E. Yorks.	Alluvial gley soil (Fluvisol) / silty clay loam	Alluvium over Quaternary glacial and lacustrine sediment	Arable	2000 / 100	0-23 24-57 58-115 116-133	1.90 1.67 1.13 0.60	46.8 61.2 87.6 14.4	Dichromate titration	Ellis & Atherton 2003
Shelford, Notts.	Stagnogley soil (Luvisol) / sandy loam	Triassic mudstone	Arable	2007	0-30 30-60 60-90 90-120	0.78 0.11 0.17 0.16	31.9 5.6 8.3 7.0	Combustion	Tye 2010
Shelford, Notts.	Brown earth (Cambisol) / silty clay loam	Triassic sandstone	Arable	2007	0-30 30-60 60-90 90-120	1.09 0.48 0.19 0.16	37.4 23.4 10.0 8.1	Combustion	Tye 2010
Shelford, Notts.	Argillic pelosol (Luvisol) / clay loam	Triassic mudstone	Arable	2007	0-30 30-60 60-90 90-120	1.00 0.20 0.15 0.13	34.0 8.5 7.3 5.1	Combustion	Tye 2010
Shelford, Notts.	Argillic brown earth (Luvisol) / clay loam	Head over Triassic sandstone	Arable	2007	0-30 30-60 60-90 90-120	1.31 0.41 0.13 0.10	50.6 18.2 5.6 5.1	Combustion	Tye 2010
Shelford, Notts.	Cambic gley soil (Gleysol) / sandy clay	Alluvial sand over Triassic mudstone	Arable	2007	0-30 30-60 60-90 90-120	1.24 0.13 0.13 0.15	44.4 5.9 4.8 4.4	Combustion	Tye 2010
Shelford, Notts.	Cambic gley soil (Gleysol) / sandy loam	Alluvial sand and gravels over Triassic mudstone	Arable	2007	0-30 30-60 60-90 90-120	2.09 0.32 0.10 ?	78.8 11.1 3.2 2.0	Combustion	Tye 2010
Shelford, Notts.	Alluvial gley soil (Fluvisol) /	Alluvial sand and	Arable	2007	0-30	3.23	120.3	Combustion	Tye 2010

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
	sandy loam	clay over Triassic mudstone			30-60 60-90 90-120	1.18 0.12 0.33	36.4 3.6 13.3		
Shelford, Notts.	Cambic gley soil (Gleysol) / sandy clay	Alluvial sand and clay over Triassic mudstone	Arable	2007	0-30 30-60 60-90 90-120	2.53 0.24 0.11 0.08	93.1 7.0 3.2 2.1	Combustion	Tye 2010
Shelford, Notts.	Argillic brown earth (Luvisol) / clay loam	Head over Triassic sandstone	Arable	2007	0-30 30-60 60-90 90-120	1.61 0.28 0.16 0.11	64.5 21.0 12.0 5.1	Combustion	Tye 2010
Shelford, Notts.	Brown earth (Cambisol) / sandy loam	Alluvial sand	Arable	2007	0-30 30-60 60-90 90-120	3.34 1.76 1.28 1.00	134.3 69.7 51.5 40.8	Combustion	Tye 2010
Shelford, Notts.	Brown earth (Cambisol) / sandy loam	Alluvial sand	Arable	2007	0-30 30-60 60-90 90-120	1.86 0.83 0.90 0.67	69.2 30.9 32.7 24.8	Combustion	Tye 2010
Several locations in England	Various	Various	Arable	?	0-30 30-100	?	70 50	?	Bradley et al. 2005
Several locations in Wales	Various	Various	Arable	?	0-30 30-100	?	70 40	?	Bradley et al. 2005
Park Grass, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Grassland; unfertilised, unlimed	1999 / >300	0-23 23-46 46-69 69-92	3.31 0.88 0.49 0.54	77.9 28.2 16.2 14.7	Combustion	Jenkinson et al. 2008
Park Grass, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Grassland; fertilised, unlimed	1999 / 143	0-23 23-46 46-69 69-92	2.84 0.75 0.49 0.39	77.1 24.1 17.2 13.3	Combustion	Jenkinson et al. 2008
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; unfertilised	2006 / 109	0-3 3-6 6-9 9-12 12-15 15-18	8.69 5.57 3.66 2.83 2.76 2.30	11.9 14.6 12.4 10.5 10.3 7.6	Combustion	Hopkins et al. 2009

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
					18-21 21-24 24-27	1.80 1.81 1.15	7.5 7.5 5.1		
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; farmyard manure	2006 / 109	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	8.21 5.65 4.28 3.77 2.86 2.70 2.67 2.20 1.93	12.8 14.6 13.4 12.6 10.6 10.2 10.1 8.7 7.9	Combustion	Hopkins et al. 2009
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; N fertilised	2006 / 109	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	35.80 30.25 11.07 5.84 1.86 1.52 1.39 1.30 0.97	37.2 37.1 29.3 20.2 7.8 6.7 6.3 6.0 4.8	Combustion	Hopkins et al. 2009
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; P fertilised	2006 / 109	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	5.55 3.84 3.22 2.72 2.45 1.74 1.33 1.04 0.83	14.6 12.7 11.5 10.2 9.5 7.3 5.7 4.6 3.8	Combustion	Hopkins et al. 2009
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; N+K fertilised	2006 / 109	0-3 3-6 6-9 9-12 12-15 15-18 18-21	35.57 26.26 9.45 3.93 1.72 1.40 1.46	37.2 37.6 26.5 14.1 7.4 6.3 6.6	Combustion	Hopkins et al. 2009

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
					21-24 24-27	1.29 1.03	5.9 5.0		
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; P+K fertilised	2006 / 109	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	8.13 4.54 3.79 3.08 2.36 2.43 1.61 1.38 1.28	17.4 15.2 13.6 11.8 9.6 9.8 6.9 6.1 5.7	Combustion	Hopkins et al. 2009
Stone Creek Farm, Sunk Island, E. Yorks.	Brown calcareous alluvial soil (Cambisol) / silty clay	Alluvium over Quaternary glacial and lacustrine sediment	Grassland	2000 / 190	0-16 17-29 30-44 45-54 55-74 75-106	2.87 2.68 1.65 1.43 1.13 1.16	52.8 ? 30.5 17.2 29.0 47.1	Dichromate titration	Ellis & Atherton 2003
Sutton Common, S. Yorks.	? / silt loam	River alluvium	Grassland; wetland	2004 / ?	0-10 30-40 50-60 70-80 100-110	[a] 7.42 7.35 19.66 17.82 6.95	?	?	Douterelo et al. 2010
Abergwyngregyn, Gwynedd	? (Cambisol) / ?	?	Grassland; sheep-grazed	?	5 10 20 30 40 50 60 70	[b] 11.29 6.35 4.94 2.12 2.82 3.53 1.41 0.71	?	Combustion	Kemmitt et al. 2008
Abergwyngregyn, Gwynedd	? (Podzol) / ?	?	Grassland; sheep-grazed	?	5 10 20 30 40 50 60	[b] 9.88 6.35 4.94 2.12 1.41 0.71 0.71	?	Combustion	Kemmitt et al. 2008

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Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha⁻¹)	Method for quantifying organic C	Reference
					70	0.71			
Llanddaniel, Anglesey	? (Cambisol) / ?	?	Grassland; cattle-grazed	?	10 20 30 40 50 60 70	[b] 3.53 2.82 2.12 2.82 1.41 1.41 0.71	?	Combustion	Kemmitt et al. 2008
Mynydd Llandygai, Gwynedd	? (Podzol) / ?	?	Grassland; sheep-grazed heath	?	5 10 20 30 40 50 60 70	[b] 30.35 12.71 5.65 4.24 2.82 1.41 1.41 0.71	?	Combustion	Kemmitt et al. 2008
Near to Denbigh, Denb./Conwy	Brown earth (Cambisol) / silt and clay loam	Silurian shale	Grassland; old and ley	?	0-15 15-45	[a] 7.25 3.89	?	Loss-on-ignition	Rieuwerts et al. 2006
Near to Denbigh, Denb./Conwy	Ranker (Regosol) / silt loam	Silurian shale	Grassland; reseeded	?	0-15 15-45	[a] 7.54 5.45	?	Loss-on-ignition	Rieuwerts et al. 2006
Near to Denbigh, Denb./Conwy	Brown earth (Cambisol) / silt loam	Silurian shale	Grassland; old and ley	?	0-15 15-45	[a] 5.74 3.42	?	Loss-on-ignition	Rieuwerts et al. 2006
Several locations in England	Various	Various	Grassland	?	0-30 30-100	?	80 50	?	Bradley et al. 2005
Several locations in Wales	Various	Various	Grassland	?	0-30 30-100	?	90 50	?	Bradley et al. 2005
3 peat cores, Broomhead Moor, S. Yorks.	Peat soils (Histosols) / ?	Millstone Grit	Peat moorland	?	0-200	53-60	36.6-95.6 per 10 cm depth interval	Combustion	Rawlins et al. 2009
Numerous soil/peat cores, Moor House, Cumbria	Peat soils (Histosols) / ?	Limestone bedrock and glacial till	Peat moorland	1995-1997	0-30 30-50 50-100 >100	?	47-176 16-103 5-216 0-2397	Loss-on-ignition	Garnett et al. 2001
Near to Denbigh, Denb./Conwy	Raw peat soil (Histosol) / ?	Silurian shale	Moorland, moss and cotton grass	?	0-15 15-45	[a] 51.10 43.73	?	Loss-on-ignition	Rieuwerts et al. 2006

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
Near to Denbigh, Denb./Conwy	Stagnopodzol (Podzol) / silty clay loam	Silurian shale	Moorland, heather	?	0-15 15-45	[a] 15.95 5.68	?	Loss-on-ignition	Rieuwerts et al. 2006
Near to Denbigh, Denb./Conwy	Stagnohumic gley soil (Gleysol) / silty clay loam	Silurian shale	Moorland, rough grazing	?	0-15 15-45	[a] 26.04 10.32	?	Loss-on-ignition	Rieuwerts et al. 2006
Several locations in England	Various	Various	Semi-natural	?	0-30 30-100	?	120 170	?	Bradley et al. 2005
Several locations in Wales	Various	Various	Semi-natural	?	0-30 30-100	?	110 120	?	Bradley et al. 2005
Mark Ash Wood, Bolderwood, Hants.	Brown podzolic soil (Cambisol) / sandy silt loam	Barton Sand	Woodland; ancient oak and beech	? / >350	0-5 5-10 25-30	?	25.6 11.8 7.2	Walkley-Black	Wilson et al. 1997
Wooson's Hill Inclosure, Bolderwood, Hants.	Brown podzolic soil (Cambisol) / sandy loam	Barton Sand	Woodland; oak and beech plantation	? / 160	0-5 5-10 25-30	?	34.0 17.5 6.6	Walkley-Black	Wilson et al. 1997
Burgess' Copse, Frilsham, Berks.	Brown earth (Cambisol) / silty clay loam	London Clay	Woodland; ancient oak and beech	? / >230	0-5 5-10 25-30	?	25.2 14.0 10.4	Walkley-Black	Wilson et al. 1997
Quavies Copse, Yattendon, Berks.	Brown earth (Cambisol) / silty clay loam	London Clay	Woodland; oak and beech plantation	? / 100	0-5 5-10 25-30	?	26.4 15.9 6.8	Walkley-Black	Wilson et al. 1997
Gardener's Copse, Felix Farm, Binfield, Berks.	Brown earth (Cambisol) / sandy loam	Loess over London Clay	Woodland; ancient oak and hazel	? / >230	0-5 5-10 25-30	?	33.6 19.9 9.5	Walkley-Black	Wilson et al. 1997
Felix Farm, Binfield, Berks.	Brown earth (Cambisol) / sandy loam	Loess over London Clay	Woodland; oak plantation	? / 100	0-5 5-10 25-30	?	15.9 12.0 5.8	Walkley-Black	Wilson et al. 1997
Broadbalk wilderness, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Woodland; mixed deciduous	1999 / 118	0-23 23-46 46-69 69-92	3.45 0.97 0.71 0.56	78.0 25.6 19.4 17.3	Combustion	Poulton et al. 2003
Geescroft wilderness,	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Woodland; oak, ash	1999 / 116	0-23 23-46	2.61 0.81	63.1 23.6	Combustion	Poulton et al. 2003

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
Rothamsted, Herts.					46-69 69-92	0.61 0.38	18.6 11.7		
Llanddaniel, Anglesey	Ranker (Regosol) / ?	?	Woodland; oak	?	5 20 40 50 60 70	[b] 48.71 37.41 7.06 7.06 6.35 2.82	?	Combustion	Kemmitt et al. 2008
Several locations in England	Various	Various	Woodland	?	0-30 30-100	?	100 70	?	Bradley et al. 2005
Several locations in Wales	Various	Various	Woodland	?	0-30 30-100	?	120 80	?	Bradley et al. 2005
Mid-Wales	Brown earth (Cambisol) / ?	Lower Palaeozoic sedimentary	?	?	0-18 18-30 30-60	3.50 3.10 3.80	?	Wet combustion	Adams & Kassim 1984
Mid-Wales	Brown earth (Cambisol) / ?	Lower Palaeozoic sedimentary	?	?	0-20 20-40 40-70	3.10 2.20 3.70	?	Wet combustion	Adams & Kassim 1984
Mid-Wales	Brown earth (Cambisol) / ?	Lower Palaeozoic sedimentary	?	?	4-18 23-53 53-83	6.50 4.60 5.60	?	Wet combustion	Adams & Kassim 1984
Mid-Wales	Brown earth (Cambisol) / ?	Lower Palaeozoic sedimentary	?	?	4-14 14-20 20-60	6.80 4.80 5.80	?	Wet combustion	Adams & Kassim 1984
Mid-Wales	Ironpan stagnopodzol (Podzol) / ?	Lower Palaeozoic sedimentary	?	?	4-15 15-23 24-37 37-58	27.00 9.70 5.50 7.40	?	Wet combustion	Adams & Kassim 1984
Mid-Wales	Stagnopodzol (Podzol) / ?	Lower Palaeozoic sedimentary	?	?	0-20 20-27 28-40 40-70	28.00 10.00 4.40 6.30	?	Wet combustion	Adams & Kassim 1984
Mid-Wales	Stagnogley soil (Luvisol) / ?	Lower Palaeozoic sedimentary	?	?	1-21 22-32 32-84	2.80 2.20 1.30	?	Wet combustion	Adams & Kassim 1984
Mid-Wales	Stagnogley soil (Luvisol) / ?	Lower Palaeozoic	?	?	0-23	1.90	?	Wet	Adams &

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
		sedimentary			23-40 40-80	1.40 1.80		combustion	Kassim 1984
Mid-Wales	Stagnohumic gley soil (Gleysol) / ?	Lower Palaeozoic sedimentary	?	?	0-38 38-48 48-84	24.00 11.00 3.80	?	Wet combustion	Adams & Kassim 1984
8 CEH Environmental Change Network Terrestrial sites (repeat sampling)	Various	Various	Various	Begun 1993, thereafter 5-yearly core (horizons, organic C) and 20- yearly pit (horizons, bulk density, organic C) sampling.	5-yearly 0-5 5-10 10-20 20-30 20-yearly 0-5 5-10 10-20 20-40 40-60 60-80 80-100 100-120	?	?	Dichromate digestion	http://www.ecn.ac.uk

Notes:
? Unknown
[a] Total organic matter measured, assumed to contain 58% C
[b] Manually read from a graph

Appendix 2. Evidence of the current status of subsoil C in global soils comparable to those in England and Wales.

Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
SCRI, Dundee, Scotland	Cambisol / sandy loam	Colluvial sand	Arable, conventional tillage	2008 / 5	0-5 5-10 10-20 20-30 30-40 40-60	2.49 2.51 2.63 2.44 1.92 1.36	15.2 15.3 36.5 35.1 27.8 34.5	Elemental analyser	Sun et al. 2011
SCRI, Dundee, Scotland	Cambisol / sandy loam	Colluvial sand	Arable, deep plough	2008 / 5	0-5 5-10 10-20 20-30 30-40 40-60	2.36 2.45 2.39 2.57 2.15 1.18	15.6 16.2 33.0 35.4 31.0 33.5	Elemental analyser	Sun et al. 2011
SCRI, Dundee, Scotland	Cambisol / sandy loam	Colluvial sand	Arable, zero tillage	2008 / 5	0-5 5-10 10-20 20-30 30-40 40-60	2.99 2.69 2.47 2.63 1.88 1.50	20.0 18.0 32.3 34.4 23.3 37.5	Elemental analyser	Sun et al. 2011
SCRI, Dundee, Scotland	Cambisol / sandy loam	Colluvial sand	Arable, minimum tillage	2008 / 5	0-5 5-10 10-20 20-30 30-40 40-60	2.90 2.76 2.81 2.65 1.99 1.69	18.1 18.1 37.6 35.0 24.5 40.5	Elemental analyser	Sun et al. 2011
Beechgrove, Bush Estate, Midloth., Scotland	?	?	Arable, no-tillage	1999 / 3	0-5 25-30	[a] 3.50 2.20	?	Elemental analyser	Vinten et al. 2002
Beechgrove, Bush Estate, Midloth., Scotland	?	?	Arable, deep plough	1999 / 3	0-5 25-30	[a] 2.70 2.30	?	Elemental analyser	Vinten et al. 2002
INRA, Versailles, France	Cambisol / sandy silt loam	?	Arable, maize	2007 / 10	5-10 80-100	[a] 1.26 0.34	?	?	Salomé et al. 2010
Mortagne-du-Nord, France	Cambisol / sandy loam	Tertiary sand	Arable, wheat-maize rotation	?	0-30 30-35 35-45 45-60	1.80 2.20 0.30 0.20	82.1 18.7 5.0 5.0	ISO 142-35	Leguédois et al. 2004

Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
Hoeilaart and Brakel, Belgium	Luvisol / silty clay loam	?	Arable	2000 / ?	0-10 20-30	1.30 0.90	?	Combustion	Lettens et al. 2007
Lommel and Brasschaat, Belgium	Podzol / loamy sand	?	Arable	2000 / ?	0-10 20-30	2.30 2.30	?	Combustion	Lettens et al. 2007
Höhere Landbauschule, Rotthalmünster, Germany	Luvisol / silt loam	Loess	Arable, wheat	2002 / 33	0-30 30-45	1.20 0.45	?	Elemental analyser	Helfrich et al. 2007
Höhere Landbauschule, Rotthalmünster, Germany	Luvisol / silt loam	Loess	Arable, maize	2002 / 23	0-30 30-45	1.30 0.68	?	Elemental analyser	Helfrich et al. 2007
Mehrstedt, Thuringia, Germany	Vertisol / silty clay loam	Limestone and loess	Arable, cereal-bean rotation	2004 / ?	0-5 5-10 10-20 20-30 30-40 40-50	?	[b] 15.9 18.1 18.8 18.1 17.7 14.8	Combustion	Don et al. 2009
Kaltenborn, Thuringia, Germany	Arenosol / loamy sand	Sandstone	Arable, wheat-maize rotation	2004 / ?	0-5 5-10 10-20 20-30 30-40 40-50 50-60	?	[b] 13.9 15.4 16.1 11.0 4.4 3.3 4.8	Combustion	Don et al. 2009
Ewiger Roggenbau, Halle, Germany	Phaeozem / sandy loam	Loess	Arable; rye, unfertilised	2000 / 122	20-40 40-60	0.78 0.40	27.0 14.2	Elemental analyser	Helfrich et al. 2010
Ewiger Roggenbau, Halle, Germany	Phaeozem / sandy loam	Loess	Arable; rye, fertilised	2000 / 122	20-40 40-60	0.87 0.42	29.8 14.8	Elemental analyser	Helfrich et al. 2010
Ewiger Roggenbau, Halle, Germany	Phaeozem / sandy loam	Loess	Arable; maize, unfertilised	2000 / 39	20-40 40-60	0.98 0.59	33.8 20.9	Elemental analyser	Helfrich et al. 2010
Ewiger Roggenbau, Halle, Germany	Phaeozem / sandy loam	Loess	Arable; maize, fertilised	2000 / 39	20-40 40-60	0.96 0.74	32.9 26.0	Elemental analyser	Helfrich et al. 2010
Bad Lauchstaedt, Germany	Chernozem / silty clay loam	Loess	Arable, rotation	2000 / ?	0-30 30-60	1.80 1.00	72.9 40.5	?	Kuka et al. 2007

Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
					60-200	0.15	28.4		
Prague Ruzyně, Czech Rep.	Luvisol / silty clay loam	?	Arable, rotation	2000 / >45	0-30 30-60 60-200	1.21 0.90 0.10	42.8 38.3 16.8	?	Kuka et al. 2007
Lincoln Farm, Canterbury, New Zealand	? (Ochrept) / loam	?	Arable, barley	1993 / 16	0-2.5 2.5-5 5-10 10-15 15-20	[b] 2.89 2.89 2.89 2.89 2.96	?	Walkley-Black	Haynes 1999
1271 profiles from 3 databases (USA, Canada, global)	?	?	Arable	?	0-20 20-40 40-60 60-80 80-100 100-200 200-300	?	45.9 25.8 16.8 13.4 10.1 3.8 2.7	?	Jobbágy & Jackson 2000
Langhill Farm, Edinburgh, Scotland	Cambisol / ?	?	Grassland; grazed	?	0-8 8-16 16-24 24-32	6.59 4.93 4.47 2.73	52.2 56.0 51.5 32.1	Loss-on-ignition	Fang & Moncrieff 2005
INRA Massif Central, France	Cambisol / ?	?	Grassland	2003 / >50	0-20 20-40 40-60 60-80 80-100	3.19 2.94 2.39 2.33 2.13	56 56 43 45 40	?	Fontaine et al. 2007
Lusigan, France	Cambisol / loam	?	Grassland	? / >50	30 60 90	0.87 0.35 0.32	53 13 9	Combustion	Sanaullah et al. 2011
Hoeilaart and Brakel, Belgium	Luvisol / silty clay loam	?	Grassland	2000 / ?	0-10 20-30	2.30 0.80	?	Combustion	Lettens et al. 2007
Lommel and Brasschaat, Belgium	Podzol / loamy sand	?	Grassland	2000 / ?	0-10 20-30	2.40 1.90	?	Combustion	Lettens et al. 2007
Oensingen, Switzerland	Cambisol / ?	Clayey alluvial deposits	Grassland, extensive	2004 / 3	0-20 20-100	?	[a] 61.0 112.0	Combustion	Ammann et al. 2009
Oensingen,	Cambisol / ?	Clayey alluvial	Grassland,	2004 / 3	0-20	?	[a] 64.7	Combustion	Ammann et

Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
Switzerland		deposits	intensive		20-100		118.3		al. 2009
Xilin River Basin, China	? (Ustoll) / ?	?	Grassland, meadow steppe	2000 / ?	0-10 10-20 20-30	[b] 3.50 2.63 2.13	[b] 37.1 27.9 25.0	Loss-on-ignition	Wang et al. 2009
Lincoln Farm, Canterbury, New Zealand	? (Ochrept) / loam	?	Grassland	1993 / 20	0-2.5 2.5-5 5-10 10-15 15-20	[b] 6.36 5.64 4.48 3.90 2.96	?	Walkley-Black	Haynes 1999
31 profiles, New Zealand	? (Alfisols, Andisols, Entisols, Inceptisols, Ultisols) / ?	?	Grassland, dairy and drystock	2002-2005 / >30	77-100 100-110 110-130	?	[a] 138-470 111-418 96-337	Combustion	Schipper et al. 2007
121 profiles from 3 databases (USA, Canada, global)	?	?	Grassland, temperate	?	0-20 20-40 40-60 60-80 80-100 100-200 200-300	?	48.0 26.9 17.6 14.0 10.5 4.2 3.2	?	Jobbágy & Jackson 2000
Bush Estate, Midloth., Scotland	Cambisol / ?	?	Woodland; birch	?	0-8 8-16 16-24 24-32	2.80 2.44 2.08 2.01	18.8 23.0 20.1 19.8	Loss-on-ignition	Fang & Moncrieff 2005
Bush Estate, Midloth., Scotland	Cambisol / ?	?	Woodland; Scots pine	?	0-8 8-16 16-24 24-32	17.51 6.53 4.61 3.86	117.7 54.9 48.3 40.8	Loss-on-ignition	Fang & Moncrieff 2005
Griffin Forest, Perth & Kinross, Scotland	Cambisol / ?	?	Woodland; Sitka spruce	?	0-8 8-16 16-24 24-32	5.83 3.93 4.39 3.87	39.6 34.3 42.8 37.8	Loss-on-ignition	Fang & Moncrieff 2005
Hoeilaart and Brakel, Belgium	Luvisol / silty clay loam	?	Woodland	2000 / ?	0-10 20-30	6.3 1.1	?	Combustion	Lettens et al. 2007
Lommel and Brasschaat, Belgium	Podzol / loamy sand	?	Woodland	2000 / ?	0-10 20-30	5.7 2.2	?	Combustion	Lettens et al. 2007

Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
Steinkreuz, Germany	Cambisol / sandy loam	Sandstone	Woodland, beech and oak	?	0-5 5-24 24-50 50-80 85-115 115-140	8.26 0.98 0.30 0.14 0.11 0.05	35.1 27.0 7.0 6.0 2.0 0.8	Elemental analyser	Eusterhues et al. 2003; Kögel-Knabner et al. 2008
Kyffhäuser, Germany	Luvisol / silty clay loam	Loess	Woodland, deciduous	?	5-15 40-80	1.15 0.49	?	Combustion	Siregar et al. 2005; Kleber et al. 2005
Lausche, Germany	Andosol / sandy silty loam	Phonolite	Woodland, mixed deciduous	?	40-70	2.77	?	Combustion	Siregar et al. 2005; Kleber et al. 2005
Waldstein, Germany	Podzol / sandy silt loam	Granitic rock	Woodland, Norway spruce	? / 150	0-10 10-12 12-30 30-55 55-70 70-80	3.81 9.28 5.20 0.77 0.17 0.19	27.1 8.0 50.5 21.0 1.0 0.5	Elemental analyser	Eusterhues et al. 2003; Kögel-Knabner et al. 2008
Köhlerwald, Germany	Luvisol / silty clay loam	Basalt and loess	Woodland, coniferous	?	13-33 87-107	3.07 1.57	? ?	Combustion	Siregar et al. 2005; Kleber et al. 2005
Orange County, North Carolina, USA	? (Udalf) / ?	Saprolite from igneous rock	Woodland, loblolly pine	1999 / 16	0-15 15-30	[a] 1.31 0.48	[a] 19.0 6.6	Combustion	Schlesinger & Lichter 2001
60 profiles from 3 databases (USA, Canada, global)	?	?	Woodland, temperate deciduous	?	0-20 20-40 40-60 60-80 80-100 100-200 200-300	?	90.5 36.5 22.6 13.9 10.4 3.3 2.1	?	Jobbágy & Jackson 2000
123 profiles from 3 databases (USA, Canada, global)	?	?	Woodland, temperate evergreen	?	0-20 20-40 40-60	?	68.8 33.7 19.0	?	Jobbágy & Jackson 2000

Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use	Year of measurement / years under current land use	Depth (cm)	Organic C content (%)	Organic C stock (Mg ha^{-1})	Method for quantifying organic C	Reference
					60-80 80-100 100-200 200-300		13.2 10.3 3.6 2.3		
Glencorse Mains, Bush Estate, Midloth., Scotland	? / clay loam	Glacial till	?	?	100-130 131-165 166-200	0.81 0.60 0.78	42.8 36.5 52.0	Walkley-Black	Castle et al. 1999
No. 3 Field, Bush Estate, Midloth., Scotland	? / sandy loam	Glacial till	?	?	100-130 131-165 166-200	0.68 0.50 0.67	34.7 29.4 41.0	Walkley-Black	Castle et al. 1999
3 CEH Environmental Change Network Terrestrial sites in Scotland and 1 in Northern Ireland (repeat sampling)	Various	Various	Various	Begun 1993, thereafter 5-yearly core (horizons, organic C) and 20- yearly pit (horizons, bulk density, organic C) sampling.	5-yearly 0-5 5-10 10-20 20-30 20-yearly 0-5 5-10 10-20 20-40 40-60 60-80 80-100 100-120	?	?	Dichromate digestion	http://www.ecn.ac.uk
1609 individual locations, Glasgow, Scotland	Various	Various	Various urban and agricultural	2001-2002	5-20 35-50	5.80 4.20	?	Loss-on-ignition	Fordyce et al. 2006

Notes:
? Unknown
[a] Total C measured, but assumed to be all organic
[b] Manually read from a graph

Appendix 3. Evidence of the dynamics of subsoil C in England and Wales.

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use or change of land use	Years of measurement	Depth (cm)	Change in organic C content (‰ yr^{-1})	Change in organic C stock (kg ha^{-1} yr^{-1})	Method for quantifying organic C	Reference
Broadbalk, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable; long-term wheat	1893-1904; 1904-1999	0-23 23-46 46-69 69-92	+0.064;+0.009 +0.027;+0.006 +0.045; 0.000 −0.045;+0.011	+200; +20 +109; +24 +191; −2 −145; +32	Combustion	Poulton et al. 2003
Park Grass, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Grassland; long-term unfertilised, unlimed	1870-1876; 1876-1906; 1906-1999	0-23 23-46 46-69 69-92	−0.317; −0.063; +0.020 −0.050; −0.007; +0.021 0.000; −0.010; +0.015 −0.083; −0.003; +0.029	−1033; −153; +23 −183; −13; +83 0; −37; +53 −300; −10; +62	Combustion	Jenkinson et al. 2008
Park Grass, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Grassland; long-term fertilised, unlimed	1870-1876; 1876-1906; 1906-1999	0-23 23-46 46-69 69-92	−0.667; +0.067; −0.045 −0.383; 0.000; +0.006 −0.033; +0.010; +0.011 −0.050; +0.013; +0.011	−1633; +163; −55 −983; −20; +29 −50; +27; +43 −183; +47; +38	Combustion	Jenkinson et al. 2008
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; unfertilised	1982-2006	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	+0.497 +0.280 +0.075 −0.151 +0.050 +0.035 −0.075 +0.103 −0.073	−82 +18 +15 −37 +13 −51 −25 +36 −28	Combustion	Hopkins et al. 2009
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; farmyard manure	1982-2006	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	+0.152 −0.156 −0.220 −0.005 +0.238 +0.059 +0.322 +0.193 +0.179	−24 −3 −27 −1 +66 +16 +97 +63 +62	Combustion	Hopkins et al. 2009
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; N fertilised	1982-2006	0-3 3-6 6-9 9-12 12-15 15-18	−0.112 +4.502 +2.436 +1.367 −0.090 −0.253	+2 +177 +547 +432 −27 −79	Combustion	Hopkins et al. 2009

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use or change of land use	Years of measurement	Depth (cm)	Change in organic C content (‰ yr^{-1})	Change in organic C stock (kg ha^{-1} yr^{-1})	Method for quantifying organic C	Reference
					18-21	–0.185	–60		
					21-24	–0.102	–34		
					24-27	–0.076	–27		
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; P fertilised	1982-2006	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	–0.503 –0.395 –0.135 –0.124 +0.039 –0.083 –0.226 –0.168 –0.098	+4 –55 –29 –32 +11 –28 –81 –65 –40	Combustion	Hopkins et al. 2009
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; N+K fertilised	1982-2006	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	–1.403 +1.028 +1.633 +0.302 –0.189 –0.127 +0.038 +0.031 +0.002	+11 +104 +406 +106 –56 –42 +14 +12 +1	Combustion	Hopkins et al. 2009
Palace Leas, Cockle Park, Northumb.	Stagnogley soil (Luvisol) / clay loam	Carboniferous shale	Grassland; P+K fertilised	1982-2006	0-3 3-6 6-9 9-12 12-15 15-18 18-21 21-24 24-27	+0.238 –0.138 +0.124 +0.196 +0.080 +0.427 +0.182 +0.091 +0.100	+150 +43 +64 +77 +40 +158 +75 +40 +44	Combustion	Hopkins et al. 2009
Broadbalk wilderness, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable (wheat) to grassland (stubbed)	1904-1964; 1964-1999	0-23 23-46 46-69	+0.242; +0.214 +0.025; +0.043 +0.005; +0.011	+523; +366 +42; +137 +15; +23	Combustion	Poulton et al. 2003
Broadbalk wilderness, Rothamsted,	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable (wheat) to woodland	1881-1904; 1904-1964; 1964-1999	0-23 23-46 46-69	+0.183;+0.227;+0.214 +0.030;+0.032;+0.034 +0.026;+0.015;+0.029	+496; +487; +314 +87; +65; +51 +83; +48; +9	Combustion	Poulton et al. 2003

Location or experiment	Soil type SSEW Soil Group (FAO WRB Reference Soil Group) / texture class	Parent material	Land use or change of land use	Years of measurement	Depth (cm)	Change in organic C content (‰ yr^{-1})	Change in organic C stock (kg ha^{-1} yr^{-1})	Method for quantifying organic C	Reference
Herts.			(oak and ash)						
Geescroft wilderness, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Arable (beans) to woodland (mixed deciduous)	1883-1904; 1904-1965; 1965-1999	0-23 23-46 46-69	+0.143; +0.100; +0.184 +0.005; +0.030; +0.015 −0.029; +0.011; +0.034	+386; +170; +453 +10; +62; +69 −90; +11; +143	Combustion	Poulton et al. 2003
Broadbalk wilderness, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Grassland (stubbed) to grassland (grazed)	1964-1999	0-23 23-46 46-69	+0.089 −0.006 +0.009	+71 +11 +29	Combustion	Poulton et al. 2003
Park Grass, Rothamsted, Herts.	Paleo-argillic brown earth (Luvisol) / silty clay loam	Chalk-with-flints	Grassland (unlimed) to grassland (limed)	1906-1999	0-23 23-46 46-69 69-92	+0.051 +0.011 +0.010 +0.004	+88 +47 +44 +15	Combustion	Jenkinson et al. 2008

Appendix 4. Evidence of the dynamics of subsoil C in global soils comparable to those in England and Wales.

Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use or change of land use	Years of measurement	Depth (cm)	Change in organic C content (‰ yr[-1])	Change in organic C stock (kg ha^{-1} yr^{-1})	Method for quantifying organic C	Reference
31 profiles, New Zealand	? (Alfisols, Andisols, Entisols, Inceptisols, Ultisols) / ?	?	Grassland, dairy and drystock	1976-2005	77-100 100-110 110-130	?	[a] −1440 to +3905 −8792 to +2724 −4000 to +200	Combustion	Schipper et al. 2007
Mehrstedt, Thuringia, Germany	Vertisol / silty clay loam	Limestone and loess	Arable (cereal-bean rotation) to grassland	1981-2004	0-5 5-10 10-20 20-30 30-40 40-50	?	[b] +660 +251 −16 −94 −314 −314	Combustion	Don et al. 2009
Kaltenborn, Thuringia, Germany	Arenosol / loamy sand	Sandstone	Arable (wheat-maize rotation) to grassland	1975-2004	0-5 5-10 10-20 20-30 30-40 40-50 50-60	?	[b] +76 −25 −177 −50 +38 +38 −38	Combustion	Don et al. 2009
Lincoln Farm, Canterbury, New Zealand	? (Ochrept) / loam	?	Arable (cereals) to grassland (continuous)	1988-1993	0-2.5 2.5-5 5-10 10-15 15-20	[b] +3.614 +1.880 +0.578 +0.289 0.000	?	Walkley-Black	Haynes 1999
Lincoln Farm, Canterbury, New Zealand	? (Ochrept) / loam	?	Arable (cereals) to grassland (annual, conv. till.)	1988-1993	0-2.5 2.5-5 5-10 10-15 15-20	[b] +0.434 +0.145 0.000 0.000 −0.145	?	Walkley-Black	Haynes 1999
Lincoln Farm, Canterbury, New Zealand	? (Ochrept) / loam	?	Arable (cereals) to grassland (annual, zero till.)	1988-1993	0-2.5 2.5-5 5-10 10-15 15-20	[b] +2.169 +0.578 +0.289 0.000 −0.145	?	Walkley-Black	Haynes 1999
Xilin River Basin, China	? (Ustoll) / ?	?	Grassland (meadow steppe) to arable (wheat-rapeseed	1958-2000; 1972-2000	0-10 10-20 20-30	[b] −0.377;− 0.402 −0.169;− 0.089 −0.089;− 0.030	[b] −337; −327 −119; −60 −69; +30	Loss-on-ignition	Wang et al. 2009

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Location or experiment	Soil type FAO WRB Reference Soil Group (or USDA Soil Taxonomy Suborder) / texture class	Parent material	Land use or change of land use	Years of measurement	Depth (cm)	Change in organic C content (‰ yr^{-1})	Change in organic C stock (kg ha^{-1} yr^{-1})	Method for quantifying organic C	Reference
			rotation)						

Notes:

? Unknown

[a] Total C measured, but assumed to be all organic

[b] Manually read from a graph