UK land-use change and its impact on SOC: 1925–2007

M. J. Bell,[1,2] F. Worrall,[1] Pete Smith,[2] Anne Bhogal,[3] Helaina Black,[4] Allan Lilly,[4] Declan Barraclough,[5] and Graham Merrington[6]

Received 4 June 2010; revised 25 August 2011; accepted 1 October 2011; published 17 December 2011.

[1] The contribution of soil organic carbon (SOC) to atmospheric greenhouse gas (GHG) concentrations could increase due to rising temperatures, agricultural land-management, and land-use change. Here the results of a modeling study are presented, which reviews the changing patterns of UK land-use from 1925 to 2007, and estimates the contribution that these changes have had toward UK GHG emissions. The study uses a large database of SOC concentrations from which SOC stocks are estimated for land-uses typical of the UK, and combines this with literature values of transition times for SOC to adjust to a new concentration following land-use change. The model was designed to be used with limited input data, allowing the impacts of historical land-use change, lacking in site specific soil and vegetation change data to be assessed. This study suggests that from 1925 to 2007 the UK's soils have acted as a net carbon sink as a result of land-use change, sequestering a total of 102 Tg C. This represents a 5% net gain in total SOC stocks, and an average increase of 1.9 Tg C/year (inter-quartile range: 0.19–3.12 Tg C/yr). When the reported losses of SOC due to climate change are compared to the gains resulting from land-use change the UK's soils are a sink of carbon, with the gains from land-use change offsetting those due to climate change. This overall sink is the result of an increase in the area of woodland, and conversion of arable land to permanent grassland. The greatest sequestration in any one year occurred in 1993 and coincides with the introduction of set-aside. The largest SOC flux to the atmosphere occurred in 1942 following arable expansion, emitting 12.3 Tg C in one year. This flux is equivalent to almost 10% of the UK's current total GHG emissions, indicating that such land-use change should be avoided in the future if targets to reduce GHG emissions are to be met.

Citation: Bell, M. J., F. Worrall, P. Smith, A. Bhogal, H. Black, A. Lilly, D. Barraclough, and G. Merrington (2011), UK land-use change and its impact on SOC: 1925–2007, *Global Biogeochem. Cycles*, *25*, GB4015, doi:10.1029/2010GB003881.

1. Introduction

[2] The UK Climate Change Act of 2008 calls for a reduction in greenhouse gas (GHG) emissions of 80% by 2050, and a reduction in Carbon dioxide (CO_2) emissions of at least 34% by 2020 [*Ostle et al.*, 2009]. Although fossil fuel and agricultural emissions are major contributors to these high concentrations of atmospheric GHGs, the importance of carbon fluxes from soils, and their contribution to either increasing or reducing atmospheric concentrations must not be overlooked. The fact that soils store 1550 Pg C globally in the top 100 cm [*Lal*, 2008] emphasizes their importance in the global carbon cycle. Although it is recognized that this stock is very large, there is still a lot of uncertainty regarding the precise amount, with estimates ranging from 1000 to 3000 Pg C [*Schwartz and Namri*, 2002]. This uncertainty and the difficulty in quantifying global stocks stems from the use of different databases, prediction at different scales, and the spatial variability in SOC stocks [*Su et al.*, 2006; *Bell and Worrall*, 2009].

[3] Recent studies on stock changes in the soils of England and Wales suggests that soil organic carbon (SOC) losses to the atmosphere could be increasing [e.g., *Bellamy et al.*, 2005], although the extent to which this is due to climate change is not clear [*Smith et al.*, 2007a]. These reported losses refer to agricultural areas where land use has remained constant over time.

[4] Our study aims to establish the role that changing land-use has had on SOC stocks and fluxes, and to therefore clarify the likely contribution that this flux has made to UK atmospheric GHG emissions over the last 80 years. The findings will help to quantify the impacts of land use change in order to guide land-use change decisions in the future.

[1]Department of Earth Sciences, Science Laboratories, Durham, UK.
[2]Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, Aberdeen, UK.
[3]ADAS Limited, Gleadthorpe Research Centre, Mansfield, UK.
[4]Macaulay Institute, Aberdeen, UK.
[5]Environment Agency, Bristol, UK.
[6]WCA Environment Limited, Farringdon, UK.

0886-6236/11/2010GB003881

Although some studies suggest that SOC loss has increased where land-use has remained constant [*Bellamy et al.*, 2005], these losses may have been counteracted by changes in land-use over this period in other areas. It may therefore be incorrect to assume that because SOC loss has increased over time under land-use that has remained constant, that the relative contribution of CO_2 emissions from soils to atmospheric CO_2 concentrations has increased.

[5] Although several attempts have been made to estimate fluxes from SOC, and establish the environmental, climatic and land-management controls on this SOC stock, there is still a lot of uncertainty over the exact extent of this stock, and the processes by which gains/losses occur [*Schulp et al.*, 2008]. The general consensus is that land-use plays a major role [*Scott et al.*, 2002], with soils acting either as a carbon sink or a carbon source as they adjust to a new SOC content following land-use change [*Guo and Gifford*, 2002], but uncertainties in the magnitude of change remain. It is widely accepted and reported that SOC stocks differ under different land-uses, and that carbon is released during conversion from grassland or forest to arable land, and accumulated following land-use change in the opposite direction [*Howard et al.*, 1995; *Zaehle et al.*, 2007; *Post and Kwon*, 2000; *Veldkamp*, 1994; *Guo and Gifford*, 2002]. There are also large variations in reported transition times for SOC to adjust to a new concentration as a result of land-use change. Some studies assume linear transitions in soil carbon for all land-use changes over time periods of less than 20 years [e.g., *Maia et al.*, 2009], while others have adjusted these to longer time periods [e.g., *Tomlinson and Milne*, 2006], and others assume instant change [e.g., *Falloon et al.*, 2006]. The advantages of this current modeling study are that it utilizes SOC values taken from a large database, therefore increasing the range of conditions under which SOC was measured, and it also takes into account the variation in transition times between SOC values when land-use change occurs. The model is therefore an advance on the IPCC guidelines of using a single value of 20 years for duration of change [*Smith*, 2004], and should provide a better estimate as to how flux from SOC responds to land-use change.

[6] Previous methods to assess the impact of land-use change on SOC have taken the form of field measurements and computer modeling, with the development of several empirical and process-based models in recent years. Although many process-based models have been validated to show their ability to adequately simulate measured data at individual field sites [*Cerri et al.*, 2007; *Coleman et al.*, 1997; *Kaonga and Coleman*, 2008] the requirement for detailed input data relating to crop inputs, soil conditions, and environmental variables, means that much of the data needed to run these models is not available for the whole of the UK from 1925 to 2007. The direct measurement of SOC fluxes in the field has increased in recent times; however, there is no record of measurements having been taken as far back as 1925, meaning that flux estimates for this period cannot be made using this data. This study recognized the requirement for a less input intensive model capable of predicting historical SOC fluxes for the UK.

[7] The approach taken by this study allows us to assess the role of land-use change on the emission or sequestration from, or to, SOC, and to investigate whether some land-use changes will increase SOC fluxes to the atmosphere, but can still be undertaken if a simultaneous land-use change will counteract this flux. According to *Powers* [2004], there is a lack of studies looking at the effect on SOC of simultaneous land-use transitions. The approach will also allow investigation of the effects of using SOC values collected from different data sets and different locations when applying these values to a large scale study. Most importantly, the model will provide an estimate of the historical sequestration/emissions of carbon from/to the atmosphere, and the contribution of land-use change and its impact on SOC to the changes in GHG concentrations.

[8] Due to the nature of this study, and the aim to assess the contribution of historical land-use change to SOC change, it is not possible to know the vegetation carbon inputs and site specific conditions required by process-based computer models. A further aim of this study was to produce a model which could be used to guide land-owners on how past and future land-management has affected/will affect SOC stocks. It was therefore hoped that the model could be used at regional scales, to assess the impacts of land-use change over large areas. As such it was decided that the SOC concentrations used should be representative of the UK, and not specific to different regions or soils. The model is designed to be used by those without the computational ability to run memory intensive process-based/dynamic models and without training in computer programming languages, as is required to run many other SOC models [*Easter et al.*, 2007]. The requirement in process-based models for input data on soil physical properties (soil moisture, temperature, porosity etc.) and daily or monthly air temperature, rainfall and potential evapotranspiration [*Nieto et al.*, 2010; *Pumpanen et al.*, 2003] means that the historical and large scale modeling of this study could not be undertaken with such packages.

2. Approach and Methodology

[10] *Howard et al.* [1995] explain that future SOC stocks following a change in land-use can be projected using a matrix of land-use change over time and a record of SOC stocks for particular land-uses. This approach is used in the current Land Use, Land-Use Change and Forestry (LULUCF) inventory for the UK, and is also employed here. The LULUCF estimates of SOC change are however based on SOC stock values for the top 30 cm of soil, as opposed to the top 20 cm of soil in this study, making comparison of results difficult. This study considers how SOC stocks in the past have been affected by land-use change, and therefore allows us to assess the extent to which land-use change has contributed to the UK's GHG emissions over the last 8 decades.

[11] The modeling of historical fluxes of carbon from UK soils required the following information: typical SOC stocks for soils under all land-uses present in the UK, the transition time over which SOC concentrations adjust to a new SOC concentration following all land-use changes; the UK's land-use change history and direction of land-use change. These data sets and their application are described in the following sections.

2.1. SOC Flux Model

[12] The assumption was made that all SOC transitions followed first order rate kinetics. The model does not make any account for climate change over the period to enable the extent of land-use change contributions to SOC emissions, and hence to GHG emissions to be established. All %SOC values refer to the top 20 cm of soil.

[13] The approach taken here considers each transition between any combination of land-uses as a first-order kinetic process, and then that the flux from the soils is the inter-annual change in the soil carbon stock. The SOC stock for each year was calculated using equation (1) and equation (2).

$$S_{dt} = K \sum_{1}^{t} \sum_{1}^{j} \sum_{1}^{i} A_j d\left(C_i \rho_{bI} - C_j \rho_{BJ}\right) e^{-\lambda t} \qquad (1)$$

$$F_t = S_{dt-1} - S_{dt} \qquad (2)$$

Where: F_t = the flux of carbon from the UK soils in year t (tons C); S_{dt} = the carbon stock in UK soil to depth d in year t (tons C); d = the depth of the soil layer considered (m); A_j = the area of land use j that transitions to land use i (m^2); C_x = the organic carbon content of the soil in land uses i and j (%). ρ_{bx} = the bulk density of land uses i and j (kg m^{-3}); λ = the time constant for transition between land uses i and j (yr^{-1}); and K = conversation factor for equalizing units. Note that this equation is written such that negative flux (F_t) is equivalent to carbon loss from the atmosphere and addition to soil.

[14] The model was run stochastically with 100 values drawn at random based upon a uniform distribution from the ranges obtained for SOC concentration, the median values for bulk density and the median value for land-use transition decay constants.

2.2. Soil Carbon Stocks by Land-Use

[15] Calculation of SOC stocks required information on SOC concentrations and the bulk density of soils under different land-uses, as well as the depth of soil to which the SOC stock was to be calculated. All values used throughout this study refer to SOC stock change in the top 20 cm of UK soils, as this is the depth of soil in which SOC is likely to respond to land-use change [*Woomer et al.*, 2001; *Cheng and Kimble*, 2001; *Kimble et al.*, 2001].

[16] Several different land-use classification schemes exist for the land-uses found in the UK, depending on the database in which they originate. Although classified in different ways, it was considered that the majority of these land-uses are very similar in both character and SOC concentration, and could therefore be re-classified into a uniform system, so that land-use transition matrices could be constructed. The land-use classification system chosen in this study consisted of 5 categories: Arable; Temporary grassland; Permanent grassland; Woodland and Urban. These were chosen under the assumption that the majority of land-uses could be assigned to one of these categories without difficulty, and that they were representative of the majority of land-uses covered in the databases. Due to classification differences between databases, an element of subjectivity was involved in selecting which land-use classifications to include in the broad land-use categories used here. Although this subjectivity is a limitation which must be considered when interpreting the results, it was considered that modeling on a scale as large as the UK would become much more difficult if a greater number of land-use classes were ascribed. Previous modeling studies have used a similar number of land-use categories when modeling UK soil carbon stocks/fluxes [e.g., *Bradley et al.*, 2005; *Smith et al.*, 2010] and SOC concentrations are often classified in broad land-use categories [*Milne and Brown*, 1997].

[17] A database of SOC concentrations, containing a total of 24,777 soil samples was used to establish typical SOC concentrations for soils under these land-uses in the UK. This large database was amalgamated from 15 individual databases, some covering all areas of the UK, and others specific to individual countries or regions. The databases used were: National Soils Inventory (NSI) [*Falloon*, 2002], National Soils Inventory Horizon data (NSI horizon) [*Falloon*, 2003], National Soils Inventory 1984 survey (NSI 1984) [*Loveland*, 1990], National Soils Inventory 2001 survey (NSI 2001) [*Bellamy et al.*, 2005], Countryside Survey 1978 (CSS 1978) [*Black et al.*, 2002], Countryside Survey 1998 (CSS 1998) [*Haines-Young et al.*, 2000], Representative Soil Sampling Scheme (RSS) [*Webb et al.*, 2001], Scottish Executive-estimating carbon in organic soils (ECOSSE) [*Smith et al.*, 2007b], National Soils Inventory Scotland (NSIS) [*Lilly et al.*, 2009], Northern Ireland Inventory 2005 (NI 2005) [*Milne et al.*, 2007; *Tomlinson and Milne*, 2006], Northern Ireland Inventory 1995 (NI 1995) [*Milne et al.*, 2007; *Tomlinson and Milne*, 2006], Wallington [*Bell and Worrall*, 2009], Wimpole (M. Bell, unpublished data set, 2009) and English Nature Woodland data (EW Wood) [*Chambers et al.*, 1998]. Median and inter-quartile ranges were calculated for both the amalgamated and individual databases for all land-uses under consideration.

[18] All databases included the category arable and selection for this classification was straightforward. Eight of the databases did not include any soil samples from a land-use similar or representative of temporary pasture, therefore these databases were not included in this category, and for all model runs using individual databases in which this occurred, the median, and inter-quartile ranges from the amalgamated database were used. The same was true when any databases did not include any soils representative of permanent pasture or woodland.

[19] The SOC concentration of urban land is debatable and is often assumed to be zero if the soil is removed during urban land conversion, and that built up areas contain no soil [*Tomlinson and Milne*, 2006]. Others argue, however, that it will approximate the value of the land-use from which it was transformed [*Howard et al.*, 1995]. As none of the databases used here contained samples taken from a land-use representative of urban land it was assumed that a SOC concentration of 0% could be applied, based on the idea that all topsoil would be removed during ground preparation and foundation establishment. This assumption implies that all urban land is built-up, however some areas of land classified as urban may be used for recreation: parks, gardens, golf-courses, etc. These are land-uses which could be expected to retain original concentrations of SOC, and as such the limitations of assuming an urban land SOC concentration of 0% must be considered in all analysis.

[20] Data on soil bulk density was obtained in the same way as that for concentration, by amalgamation of all

Table 1. The Preferential Direction of Land-Use Change Assumed in This Study[a]

From	To 1	To 2	To 3	To 4
Arable	Improved P	Urban	Permanent P	Woodland
Improved P	Arable	Urban	Permanent P	Woodland
Permanent P	Woodland	Improved P	Arable	Urban
Woodland	Improved/ permanent P	Arable	Urban	Woodland
Urban	Improved P	Arable	Permanent P	

[a]Where 1 is the land-use most likely to have been created following a decrease in the area of the land-use being replaced, and 4 is the land-use least likely to have been created.

databases, with a median value established for each land-use in question. Although it is recognized that soil bulk density varies greatly, it was thought that use of a median value for each land-use would provide the most accurate results, as the stochastic nature of the model means that it randomly selects SOC concentrations for each specific land-use from the inter-quartile range. Stochastic selection of both bulk density and SOC concentration could result in unusually high/low SOC contents being predicted if a value at the top/bottom of the range for both SOC concentration and bulk density was selected. For this reason it was considered best to use only median values for bulk density.

[21] The amalgamated soil carbon database used in this study includes soil samples taken from all over the UK. The inter-quartile range of land-use specific SOC concentrations from which the model randomly selects is likely therefore to include samples taken from a very large range of climatic, altitudinal and soil textural conditions - all factors which can result in differing SOC stocks [*Krishnan et al.*, 2007; *Yang et al.*, 2008]. Due to a lack of knowledge concerning exact locations associated with the land-use change in question it was concluded that using these UK-wide values was the best approach to take. In an ideal situation land-use change would be modeled using precise information on the geographic location of the land-use change and SOC concentrations typical of that altitude and climate, but this would require much greater input data and computer processing capabilities. The model used in this study is run 100 times and extracts SOC concentrations from the inter-quartile range of the database and will thus have selected samples taken from a wide range of geographic locations, therefore providing a representative simulation of how land-use change in the UK will influence SOC emission/sequestration. As this model is intended to be used at a large scale and by users without access to high level computer programs and modeling packages this was considered to be the best approach to take. Although it is realized that organic soils and mineral soils have very different SOC stocks and respond differently to land-use change it was not possible to identify exactly which land-use changes occurred on which soil types. The approach of selecting from an inter-quartile range of land-use specific SOC concentrations from the UK-wide database means however that the majority of soil type/land-use combinations will be represented in the model simulations. A land-use change from pasture to woodland on mineral soils for example would likely result in sequestration of atmospheric carbon to SOC, whereas the same land-use change on organic soils could in-fact cause a release of SOC to the atmosphere. In this study the use of SOC values taken from a range of both mineral and organic soils means that the median and inter-quartile range values will have accounted for e.g., both these higher and lower SOC values under woodland compared to pasture.

[22] A median SOC value and inter-quartile range was calculated for all land-uses, for both the amalgamated database and each database individually.

2.3. UK Land Use History

[23] The change in area of land-use for the UK over the period 1925 to 2007 was reconstructed using data from several sources. The initial year of 1925 was used as this was the year of formation of the UK within its current borders. Land-use information (area of arable crops, temporary grassland, permanent grassland, bare fallow, rough grazing, common rough grazing, set-aside and urban) was available for the UK from the Ministry of Agriculture, Fisheries and Food, and the Department of Environment, Food and Rural Affairs [*Ministry of Agriculture, Fisheries and Food*, 1926–2000; *Department for Environment, Food and Rural Affairs*, 2001–2008]. Information on the area of woodland over this period was available from the Forestry Commission [*Forestry Commission*, 2007]. This woodland data was however only available for the years 1924, 1947, 1965, 1980, 1990, 1998–2002 and 2008. To get an annual estimate of woodland area linear interpolation was used between survey dates. If this assumption of a linear change in woodland area between survey dates is incorrect, and the change occurred at a faster or slower rate, then the change in SOC stocks predicted by the model will inherit these inaccuracies. This is a limitation which must be considered throughout all analysis.

[24] The land-use data provided by these sources was, as was the case with the SOC databases, classified differently to those chosen in this study. In order to fit the categories arable, temporary pasture, permanent pasture, woodland and urban the following land-use categories from the original databases were grouped as follows: arable crops, bare fallow, set aside = arable; temporary grass = temporary grassland; permanent grass, rough grazing, common rough grazing = permanent grassland; woodland = woodland; urban = urban.

[25] Although information on land-use change covering the period 1925 to 2007 was available, this only provided detail on the change in area of each individual land-use, and did not reveal the direction of land-use change from and to another land-use. Information in the literature [*Adger and Subak*, 1996; *Adger et al.*, 1992] was used to allocate which land-uses were likely to convert to other land-uses. In some situations the direction of land-use change could confidently be estimated simply by observing a simultaneous increase/decrease of similar magnitude in two land-uses, therefore reaching the consensus that the land-use with a decrease in area was likely to have lost land to the land-use with an increase in area. In all situations the work of *Adger and Subak* [1996] and *Adger et al.* [1992] was used to help identify the most likely direction of land-use change. The land-use change matrix used in this study is displayed in

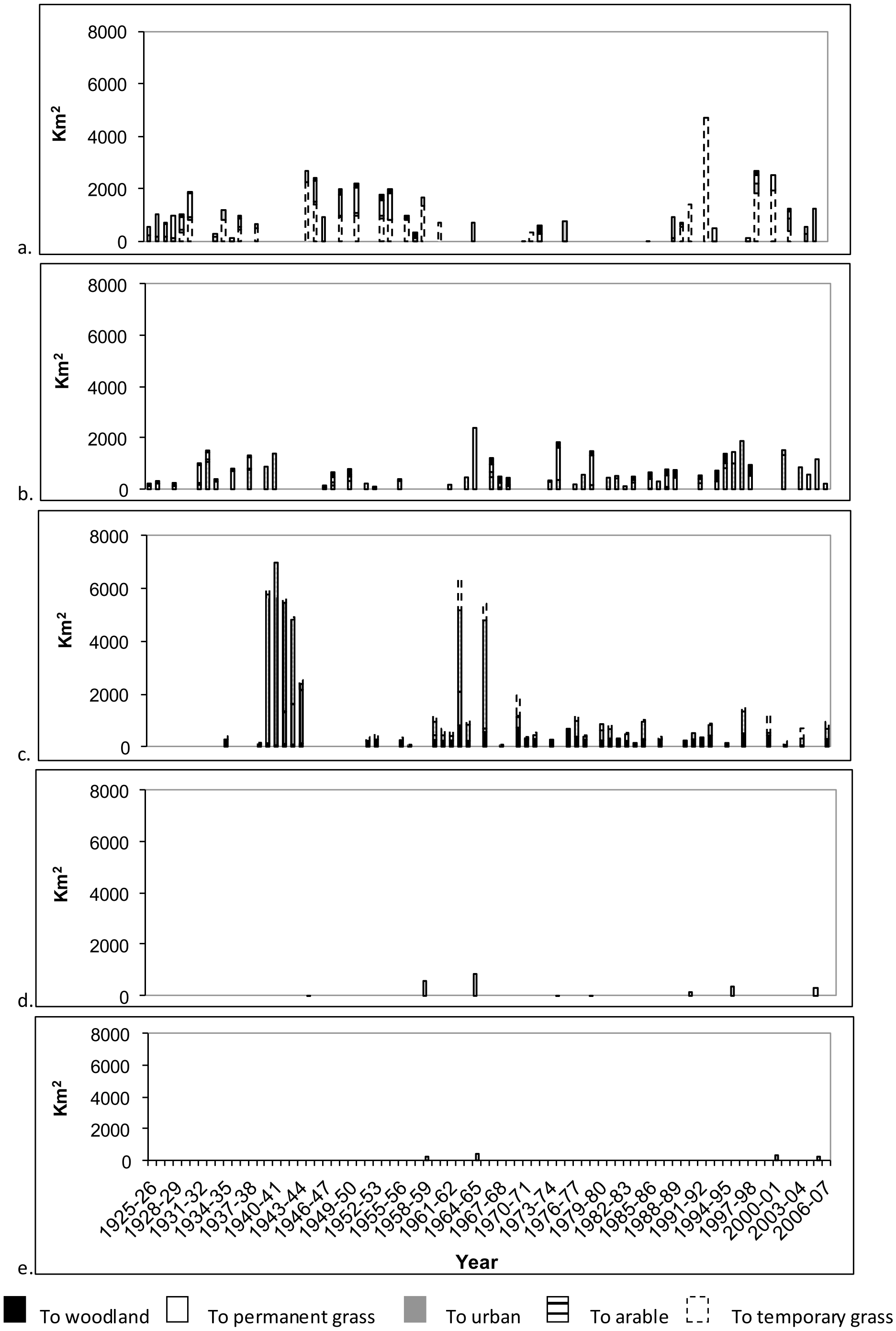

Figure 1. Predicted directions of UK land-use change, 1925–2007, (a) out of arable; (b) out of temporary grassland; (c) out of permanent grassland; (d) out of urban land; (e) out of woodland.

Table 1, indicating the preferential direction of land-use change. The limitations of making such land-use change direction assumptions must be considered during the analysis of results, as in reality all directions of land-use change are unlikely to have followed those suggested in the literature. Making these assumptions was the best method available as there was no record of the direction of land-use change available at the time of writing. It is acknowledged that all the land-use in existence in 1925 was unlikely to have been at SOC equilibrium, with some of this land likely to be adjusting from previous (unknown) land-use change. As the land-use history is not known prior to 1925 the model cannot be run to simulate the sink/source status of this land at this time. However, the average change in land uses for the decade 1925–1934 was assumed to be true if the UK had existed for the period 1915–1924, in this way equilibrium is not assumed at the start of the study period. The predicted directions of land-use change used in this study can be seen in Figure 1.

Table 2. Estimates of Decay Constants and Half-Lives, Associated With Land-Use Change Resulting in Soil Carbon Losses

Land-Use Change[a]	Reference	Estimated Half-Life (years)	Estimated Decay Constant (per year)
W to A	*Murty et al.* [2002]	4	0.17
W to A	*Bonde et al.* [1992]	6.3	0.11
W to A	*Motavalli et al.* [2000]	2.8	0.24
W to A	*Houghton and Hackler* [2000]	1.3	0.52
W to A	*West et al.* [2004]	1.8	0.39
W to A	*Murty et al.* [2002]	3.65	0.19
W to A	*Heath et al.* [2002]	1.11	0.62
W to A	*Heath et al.* [2002]	3.11	0.22
W to A	*Milne* [1999]	8.9	0.08
W to A	*Schlesinger* [1986]	5.34	0.13
W to A	*Lubowski et al.* [2005]	0	0.69
W to P	*Heath et al.* [2002]	12.5	0.06
W to P	*Milne* [1999]	50	0.01
W to P	*Lubowski et al.* [2005]	0	0.69
P to A	*Milne* [1999]	50	0.01
P to A	*U.S. Environmental Protection Agency* [2008]	2.5	0.28
P to A	*Lubowski et al.* [2005]	0	0.69

[a]W = woodland; A = arable; P = pasture.

2.4. SOC Transition Times

[26] A lack of long-term field trials measuring SOC change on a continual basis following land-use change means that there is still a large amount of uncertainty over both the transition time and the rate of transition as soils approach a new SOC concentration. There is "no consensus" as to when SOC equilibrium will be reached following land-use change- with estimates ranging from 6 years to 100 years [*King et al.*, 2004; *Smith et al.*, 1997]. Losses due to land-management change reported by *Bellamy et al.* [2005], suggest that equilibrium may in-fact never be attained.

[27] To achieve a best approximation of the transition times over which a new SOC concentration will be reached we performed a literature review to identify the most realistic outcome. Although many studies were qualitative rather than quantitative in their reference to transition times, the information provided by each study was used to establish decay constants. A lack of literature specific to the UK meant that data from other countries was also consulted. Although it is acknowledged that SOC transition times are likely to be different in different countries and climates, this data was used as it was the best available substitute. It is suggested that once more experimental data specific to the UK is made available that this data is incorporated into this study and the transition times adjusted accordingly. The majority of studies reported exponential rates of change, enabling a decay constant to be calculated if the half-life was known, using equation (3):

$$\lambda = \frac{\ln 2}{t1/2} \tag{3}$$

If studies provided information on the time taken for a new SOC concentration to be reached, but not the half-life, then an estimate of the half-life was needed before an estimate of the decay constant could be made. In a number of cases an estimate of the half-life was possible using information provided on SOC concentrations at a number of intervals over the transition period. In situations where no information was provided on %SOC concentrations at intervals over the period of transition then an estimate of the number of half-lives gained from the other literature was used to estimate the half-life, as displayed in equation (4).

$$t1/2\ \ estimate = \frac{no.\ of\ years\ for\ new\ SOC\, concentration\ to\ be\ reached}{mean\ no.\ of\ t\ 1/2s\ taken\ for\ new\ SOC\ concentration\ to\ be\ reached} \tag{4}$$

The estimated decay constants from the literature review are displayed in Tables 2 and 3.

[30] The decay constants from each study were combined to obtain a median decay constant for each land-use change transition. The lack of information in previous studies relating to transition times meant that when transition times were referred to it was very unlikely that they were specific to temporary and permanent pasture, with the majority of cases only referring to the land-use as pasture. All land-use transitions into or out of both temporary and permanent pasture were therefore ascribed the same values. Although this was considered to be the best assumption to make, given the available data, it must be realized that more confidence could be given to the results of the model if evidence showing the similarity in these transitions rates can be made. In the case of a land-use change into urban land it was considered that the change would occur immediately, as the soil would be removed from the site and all SOC would disappear instantly. In terms of transitions out of urban and into arable or pasture it was assumed that the transition would occur at a similar rate to that of a transition from arable to pasture, due to a similar extent of SOC change associated with such a land-use change. Although a large number of studies looked at transition times associated with arable to woodland, there was a lack of studies looking at any other change from woodland. It was therefore assumed

Table 3. Estimates of Decay Constants and Half-Lives, Associated With Land-Use Change Resulting in Soil Carbon Gains

Land-Use Change[a]	Reference	Estimated Half-Life (years)	Estimated Decay Constant (per year)
A to W	*Houghton and Hackler* [2000]	13.4	0.05
A to W	*Post and Kwon* [2000]	37.5	0.02
A to W	*Poulton et al.* [2003]	60	0.01
A to W	*Falloon et al.* [2004]	50	0.01
A to W	*Milne* [1999]	100	0.01
A to PW	*Falloon et al.* [2006]	0	0.69
A to PW	*Grogan and Matthews* [2001]	51	0.01
A to PW	*Andress* [2002]	40	0.02
A to PW	*Heath et al.* [2002]	25	0.03
A to PW	*Heath et al.* [2002]	47.5	0.01
A to PW	*Zak et al.* [1990]	25	0.03
A to P	*U.S. Environmental Protection Agency* [2008]	10	0.07
A to P	*Lubowski et al.* [2005]	18.1	0.04
A to P	*Lee et al.* [2005]	15	0.05
A to P	*Falloon et al.* [2004]	25	0.03
A to P	*Jenkinson et al.* [1987]	17.5	0.04
A to P	*Milne* [1999]	100	0.01

[a]W = natural woodland; PW = planted woodland; A = arable; P = pasture.

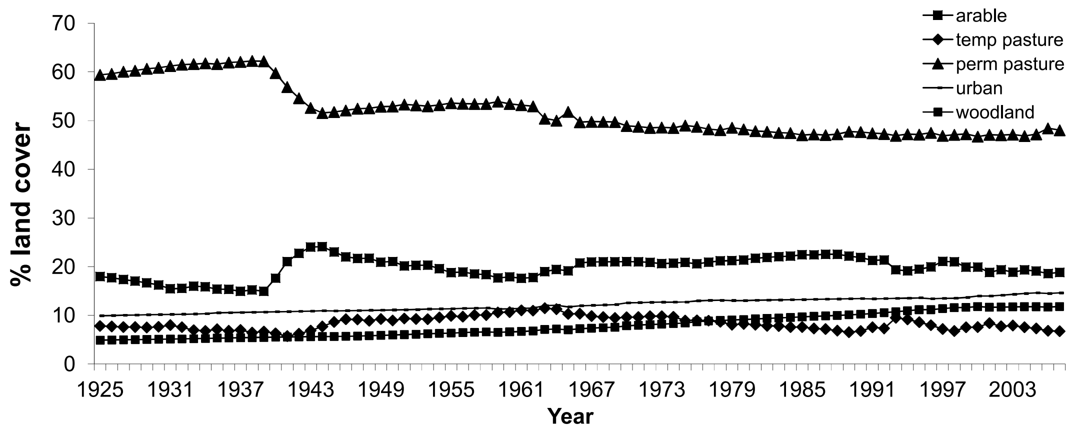

Figure 2. UK land-use change 1925–2007.

that these transitions would occur at similar rates. A lack of information on transition times in the literature, and a lack of measured data, means that these assumptions were made as they were considered to be the best approach available.

2.5. Sensitivity/Uncertainty Analysis

[31] In addition to the model run using the amalgamated database, simulations were also undertaken using several of the regional and country specific databases, in order to compare outputs generated using different SOC values.

3. Results

3.1. UK Land Use Change 1925–2007

[32] The percentage of land under both permanent and temporary pasture is lower in 2007 than in 1925 (Figure 2). There was a slight increase in permanent pasture until 1939, followed by a sharp decrease into the early 1940s, and a steady decline thereafter. Permanent pasture at the beginning of this time period covered approximately 59% of the UK land area, and now covers less than 49%. The area under temporary pasture has fluctuated over the period, and has covered a significantly smaller area than permanent pasture throughout. Figure 1 displays several transitions out of temporary pasture over the period, with a notable transition to permanent pasture in the 1960s. The land area under arable crops has been second only to permanent pasture throughout the period, and has generally followed a reverse trend to that of permanent pasture, with a large increase in area in 1939, followed by several fluctuations in reverse to that of either permanent pasture or temporary pasture. Other notable fluctuations in arable land area were an increase in

Table 4. Databases Used to Predict SOC Concentrations (% SOC) Under Different Land-Uses

	Database[a] (Number of Samples)															
	All (24777)	RSS (9961)	NSI 1984 (5121)	NSI 2001 (2143)	NSI Invent (1543)	NSI Horizon (1136)	Ecosse (973)	CSS 1978 (867)	CSS 1998 (841)	Wallington (598)	NI 2005 (484)	NI1995 (457)	NSIS (312)	Wimpole (282)	EW Wood 2001 (90)	EW Wood 1971 (90)
	Arable % SOC															
median	2.17	1.94	2.20	2.06	2.06	2.30	4.02	2.50	2.47	2.73	3.88	4.17	3.31	2.01		
lower Q[b]	1.50	1.37	1.50	1.57	1.59	1.70	3.00	2.00	1.94	2.28	2.44	2.42	2.23	1.71		
upper Q[c]	3.07	2.62	3.30	2.73	2.74	3.10	5.12	3.50	3.36	3.20	5.06	5.48	4.18	2.42		
	Temporary Grass % SOC															
median	2.74	2.57	3.20	3.04	3.30	2.70				2.93			4.14			
lower Q	2.05	1.94	2.30	2.29	2.36	2.00				2.30			3.11			
upper Q	3.76	3.36	4.60	3.88	5.53	3.60				3.26			5.68			
	Permanent Grass % SOC															
median	4.40	4.22	4.70	4.17	3.22	4.00	5.42	4.50	5.05	3.87	6.15	5.20	7.40	3.64		
lower Q	3.24	3.14	3.30	3.08	2.34	3.00	4.40	3.00	3.66	3.13	4.38	3.90	4.65	3.10		
upper Q	6.02	5.36	7.40	6.06	4.40	5.50	6.52	8.00	7.88	4.93	11.0	8.31	2.71	4.38		
	Woodland % SOC															
median	7.00		4.80	5.10	5.94		30.5	7.00	9.60	27.2	50.5	42.1		4.73	9.12	8.21
lower Q	4.20		2.93	3.32	4.24		18.55	5.70	5.70	16.71	10.78	30.30		4.15	6.80	6.44
upper Q	17.63		7.70	7.75	10.0		40.48	27.68	27.68	33.74	53.70	46.03		5.79	11.54	11.09

[a]All = all databases combined; RSS = Representative Soil Sampling Scheme; NSI = National Soils Inventory; NSI Horizon = National Soils Inventory Horizon; Ecosse = Scottish Executive: Estimating Carbon in Organic Soils; CSS = Countryside Survey; NI = Northern Ireland; NSIS = National Soils Institute of Scotland; EW = English Nature woodland data.

[b]Lower Q = lower quartile.

[c]Upper Q = upper quartile.

Table 5. Soil Organic Carbon, Soil Bulk Density and Soil Depth Values Used in Model

	% SOC	Bulk Density (g/cm^3)	Depth (cm)
Arable	1.50–3.07	1.22	20
Temporary grassland	2.05–3.76	1.22	20
Permanent grassland	3.24–6.02	1.02	20
Urban	0	1.22	20
Woodland	4.20–17.63	0.58	20

Table 6. Soil Organic Carbon Decay Constants With a Change in Land-Use A to Land-Use B

	Land-Use B				
Land-Use A	Arable	Temporary Grassland	Permanent Grassland	Urban	Woodland
Arable	0.00	0.04	0.04	0.69	0.02
Temp	0.28	0.00	0.03	0.69	0.02
Perm	0.28	0.33	0.00	0.69	0.02
Urban	0.03	0.04	0.04	0.00	0.02
Woodland	0.06	0.06	0.06	0.69	0.00

the early 1960s and a decrease in 1991. Land area under urban usage has increased very steadily over the period, retaining its position as the third greatest land-cover. Since 1925 it has gained approximately 50% of its original land area- increasing its percentage cover from 10% to approximately 15% by 2007. Land area under woodland increased most rapidly in the early 1960s and then at a steady and constant rate thereafter, to replace temporary pasture as the fourth most important land cover, resulting in a more than 50% increase in its percentage cover from 5% to greater than 10%.

3.2. SOC Concentrations by Land-Use

[33] There was an increase in SOC concentrations with land-use in the order: urban < arable < temporary pasture < permanent pasture < woodland (Tables 4 and 5). SOC values for the same land-use did however differ between databases (Table 4). This is to be expected due to some databases being regionally specific (e.g., Wallington) and others being specific to countries with large areas of organic and peat soils (e.g., NI and NSIS). It should also be noted that given the ranges of observed values it is possible that some land-use changes that would most commonly result in a SOC decrease may on occasion result in an increase and vice versa.

3.3. SOC Transition Times

[34] Figure 3 shows the variation in transition times depending on the land-use change in question, with SOC gains occurring at a slower rate than SOC losses. It can also be seen that the transition times used in this model differ greatly from the 20 year linear change assumed (as a global simplification) by the IPCC [see *Smith*, 2004]. Transition times used in this study are outlined in Table 6.

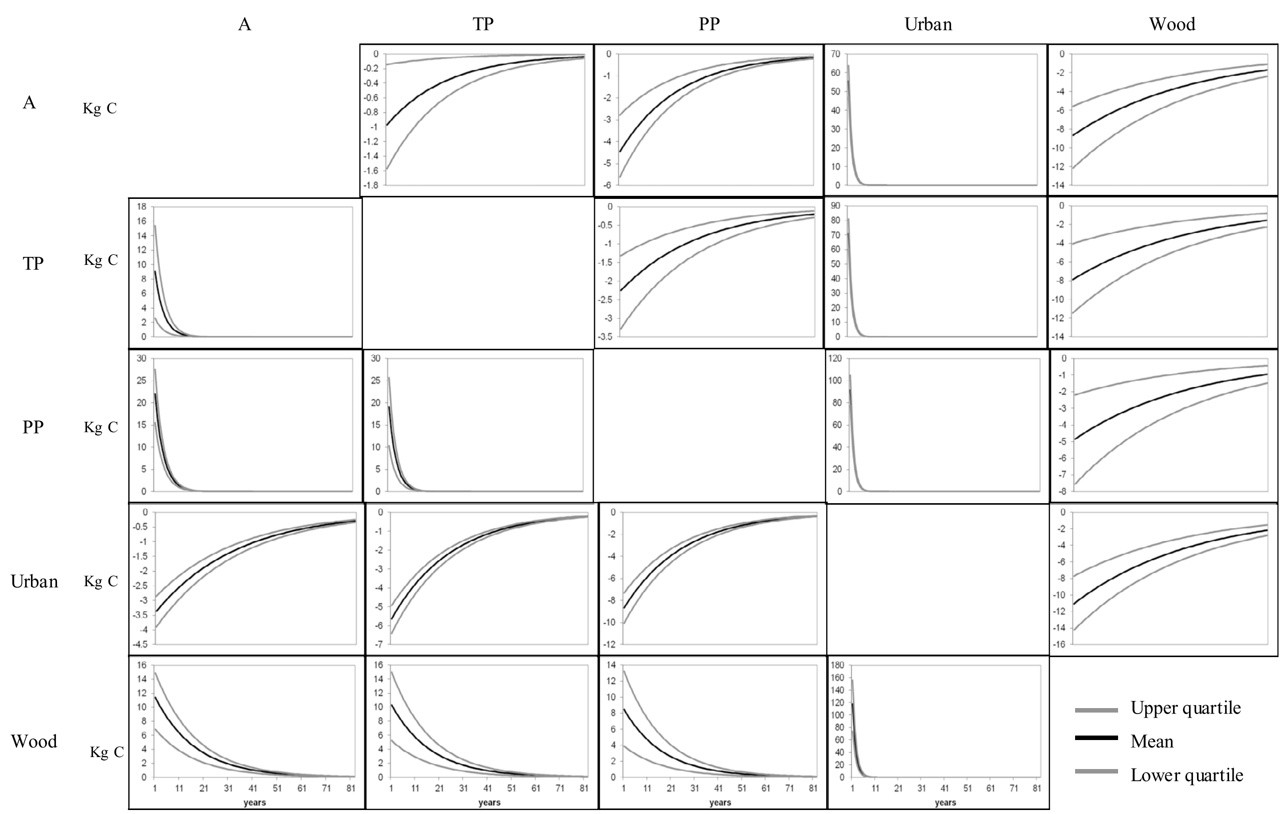

Figure 3. Rate and direction of UK soil organic carbon change following land-use transitions. The land-use change transition refers to a change from the horizontal land-use to the vertical land-use column. A = arable; TP = temporary grassland; PP = permanent grassland; wood = woodland.

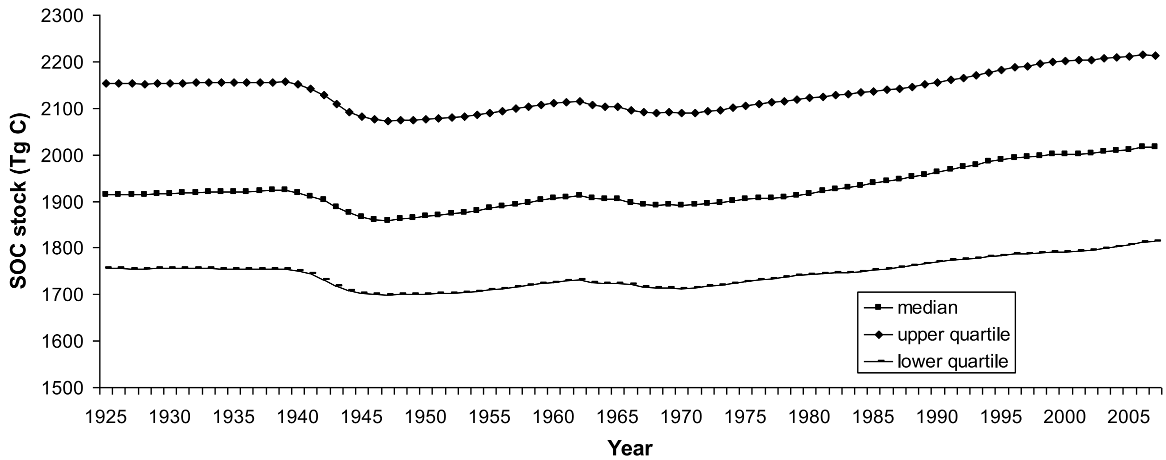

Figure 4. The modeled change in UK soil organic carbon stock: 1925–2007.

3.4. SOC Flux

[35] The model predicts a 5% net gain in SOC stocks between 1925 and 2007 due to land-use change (Figure 4), representing a gain of 102 Tg C. This equates to a median flux into the soil of 1.92 Tg C/year (inter-quartile range: 0.19–3.12 Tg C/year.) The greatest sink in any one year took place in 1993, with a flux into the soil from the atmosphere of 4.31 Tg C. The greatest loss of SOC to the atmosphere occurred in 1942, with a flux to the atmosphere of 12.3 Tg C. Other noticeable periods of carbon sequestration were during the entire decade of the 1950s, and for at least 20 years from 1970 into the early 1990s. Other than the emissions of 1942 there were also large fluxes of SOC to the atmosphere in 1961, 1964 and 2005. Examination of Figure 5 reveals that from 1970 to 1994 the UK's SOC flux resulting from land-use change remained relatively constant, sinking an average of 3.10 Tg C/yr, representing a net gain in SOC stock of 0.2% per year. This trend, however, may be beginning to decline, with a gradual decrease in the extent of the carbon sink appearing from 1994 onwards, with an average sink of only 2.00 Tg C/yr, a gain of only 0.12% per year. The extent of the flux caused by transitions into and out of various land-uses over the entire period is compared in Figure 6. The change in SOC stock over the entire period is shown in Figure 4, and the timing and direction of yearly fluxes can be seen in Figure 5. The cumulative SOC flux from land-use change is shown in Figure 7.

[36] Predicted SOC fluxes differed greatly depending on the database used (Figure 8), with the greatest total flux over the period predicted from the Wallington database, where a net gain in SOC content of 13.8% is compared to only 2.74% using the NSI values.

[37] The model used in this study predicts a 4.81% net gain in SOC stocks between 1978 and 2003 due to land use change, representing a SOC gain of 96.57 Tg C (3.86 Tg C/yr). This sink is greater than the maximum estimated loss of 2.5 Tg C/yr caused by climate change [*Smith et al.*, 2007a], suggesting that the carbon sequestered from land-use change will have offset that lost as a result of climate change. This sequestration of 3.86 Tg C/yr from

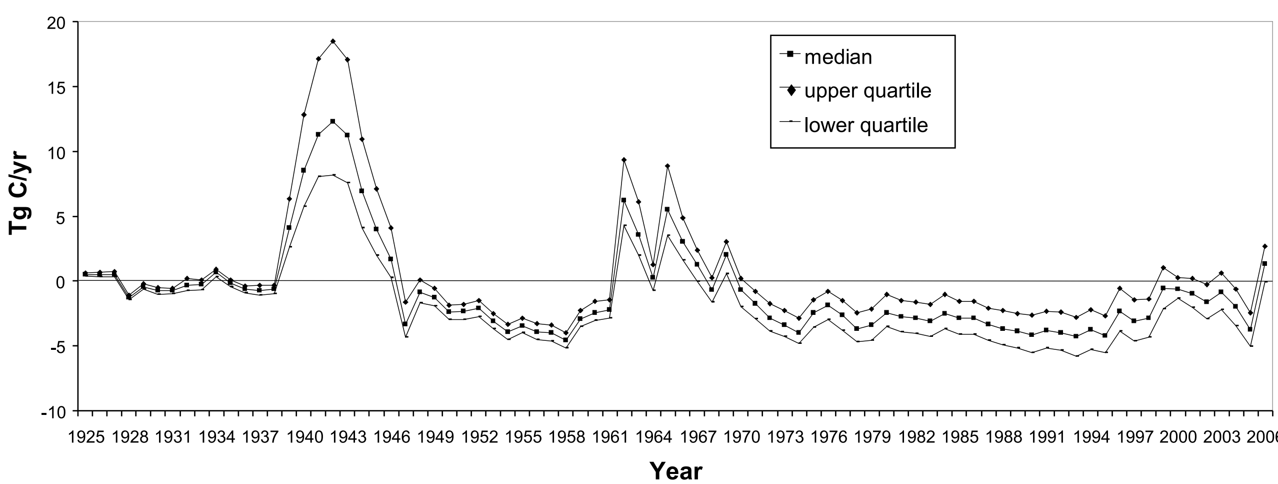

Figure 5. The modeled flux of UK soil organic carbon from 1925–2007 resulting from land-use change. A positive flux represents a flux from the soil to the atmosphere; a negative flux represents a flux from the atmosphere into the soil.

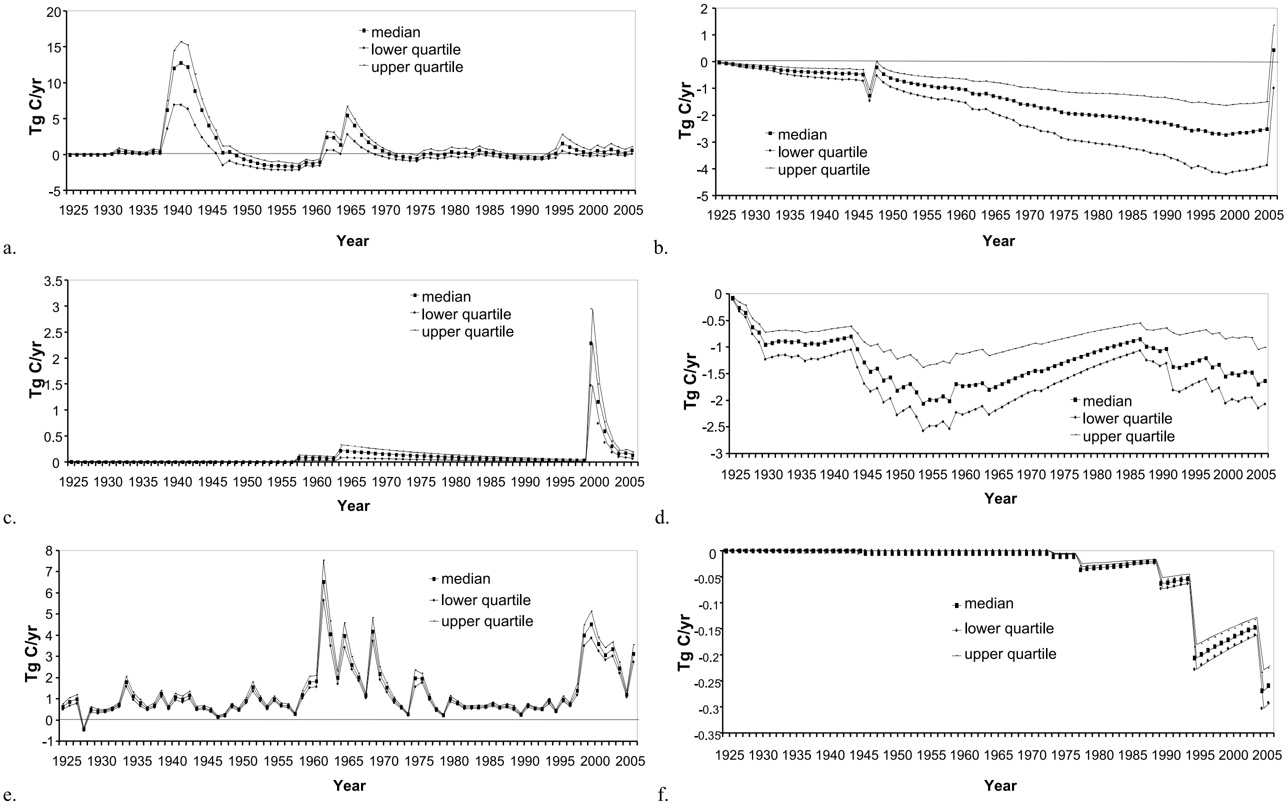

Figure 6. The extent and direction of the overall soil organic carbon flux caused by various land-use change transitions. (a) Land-use change from grassland to arable; (b) land-use change into woodland; (c) land-use change out of woodland; (d) land-use change from arable to grassland; (e) land-use change into urban; (f) land-use change out of urban.

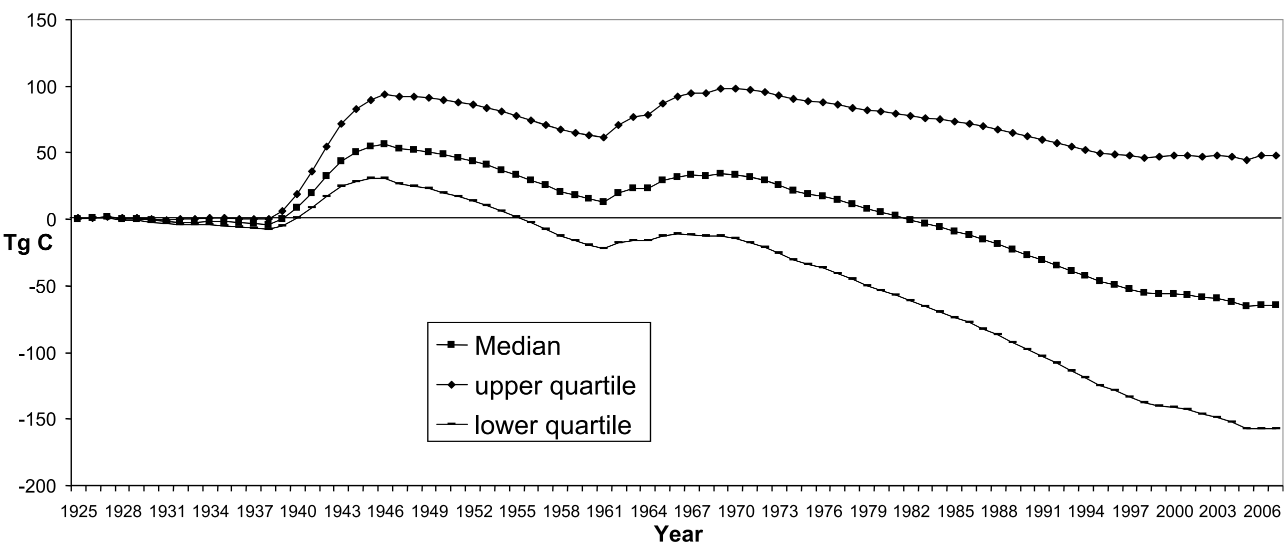

Figure 7. The UK's cumulative soil organic carbon flux: 1925–2007. A positive flux represents a flux from the soil to the atmosphere; a negative flux represents a flux from the atmosphere into the soil.

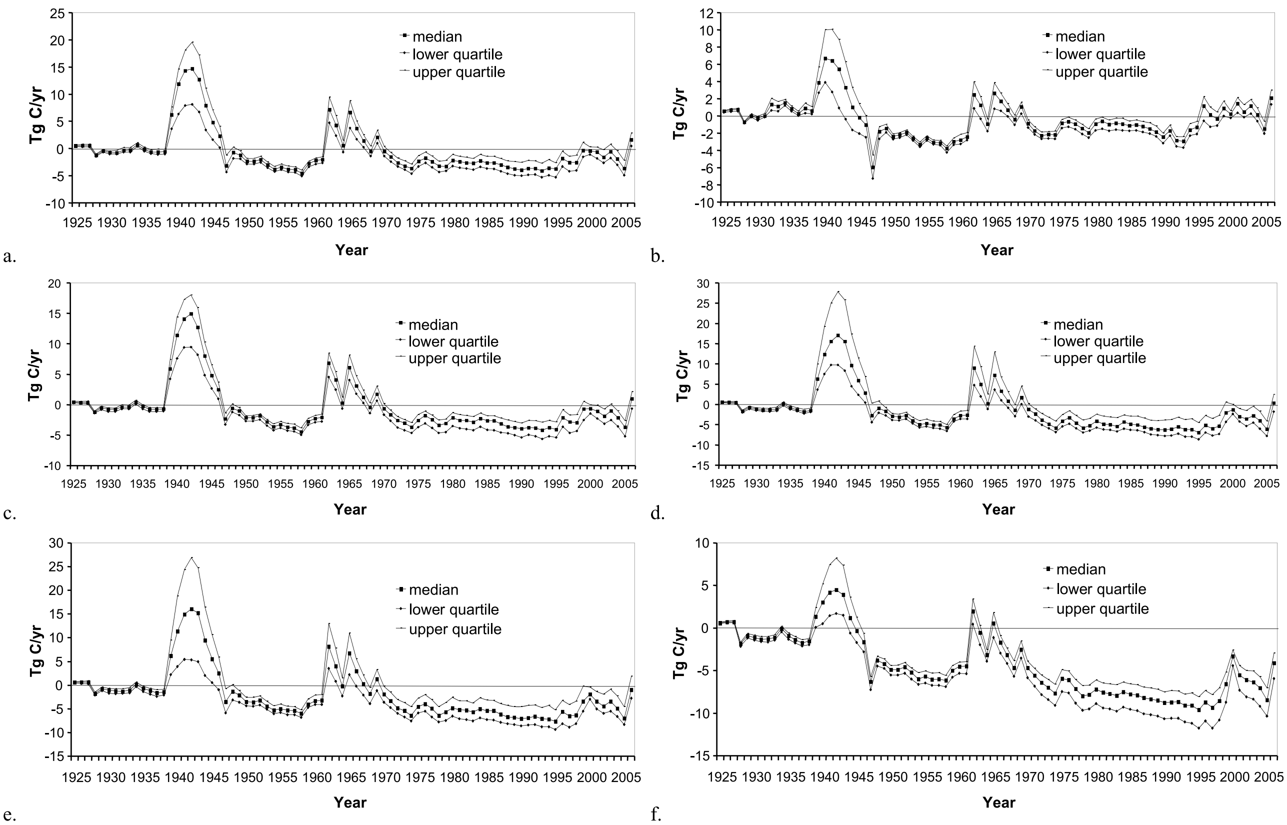

Figure 8. The difference in modeled outputs resulting from the use of various soil organic carbon databases. (a) Amalgamated databases; (b) National Soils Institute Inventory database; (c) RSS database; (d) Countryside Survey database 1998; (e) Countryside Survey 1978 database; (f) Wallington database.

1978 to 2003 is also large enough to have offset some of the losses caused by land-management change over this period [*Bellamy et al.*, 2005], decreasing the total emissions to the atmosphere. The model used in this study predicts a gain of 28.0 Tg C over the period 1984–1990, in comparison to *Howard et al.*'s [1995] estimated loss of 32.6 Tg C.

4. Discussion

[38] From initial observation of the changing land-use from 1925–2007 (Figure 2), one might expect that the UK will have been a source of SOC to the atmosphere, due to the decrease in area of permanent pasture, increase in area of urban land, and very slight increase in arable area. The results presented above, however, indicate that this was not the case, and that the UK's soils have been a net sink of carbon. Figure 6 suggests that the majority of this sink is the result of land-use change into woodland, and conversion of arable land to permanent grassland. The greatest SOC loss to the atmosphere in 1942 of 12.3 Tg C can be explained by the large increase in arable land as a result of government persuasion to plough up large areas of permanent grassland [*Holderness*, 1985] during World War II. Two other large fluxes to the atmosphere caused by land-use change are evident in Figure 5, for the years 1961 and 1964, and could also correlate with a second phase of arable expansion. Figure 6, however, shows that some of these emissions were also the result of urban expansion. The modeling of individual land-use change shows that both carbon sequestration and carbon emission were occurring simultaneously at this time, and that some of the emissions from urbanization and arable expansion were being compensated for by the sinks associated with land-use change to woodland and conversion of arable land to grassland. Had the latter changes not occurred, the flux to the atmosphere would have been of an even larger magnitude. The greatest gain in SOC in 1993 could be in part the result of the introduction of set-aside in the UK, in agreement with the situation in the U.S., where set aside has been responsible for a net increase in SOC [*Ogle et al.*, 2009]. Although voluntary set-aside began in 1988, it was in 1993 that the Arable Area Payments Scheme came into force [*Adger and Subak*, 1996]. Investigation into the fluxes caused by arable to grass conversion (Figure 6), however, reveals that although there was an amount of sequestration caused by this land-use change, it equated to only 1.38 Tg C. This is similar to the figure of 0.8 Tg C quoted by *King et al.* [2004] for conversion of arable land to set-aside. The large emission in 2005, and the general decreasing trend in carbon sequestration from 1994 to the present-day can be explained by changes out of grassland, out of woodland and land-use changes into urban land (Figure 6).

[39] The results of this modeling study not only provides information on how much of our GHG emissions over the last century can be ascribed to SOC, but may also help guide our future land-use change decisions. These results

emphasize the importance of considering simultaneous land-use change decisions and how some SOC fluxes may be counteracted or added to by other land-use changes then or within a few years. This is important in terms of reacting to the current increases in GHG emissions, and the need to realize that what occurs in a single year can cause large emissions, and that these should be avoided given the aims to reduce GHG emissions. The model allows us to assess land-use change contribution to CO_2 emissions or sequestration on a yearly basis from 1925 to 2007, therefore revealing carbon fluxes that would otherwise be obscured if only the change in SOC flux at the beginning and end of the period were measured. The extent of the fluxes caused by some land-management changes (e.g., the emissions of 1942) may have been missed if this approach had been taken, due to counteraction by fluxes in the opposite direction in later years. Although *Tomlinson and Milne* [2006] assessed soil carbon changes from 1939 to 2000 in Ireland, they did this assuming that the total changes in land-use over this period occurred at an equal rate over the period. Such an approach does not therefore reveal the consequences of a rapid flux, such as that of 1942 in the UK, and cannot inform our understanding of the short-term effects of any such rapid changes in the future. Although some of the process-based models described in the introduction are capable of predicting the effects of multidirectional land-use change on an annual basis, the high input requirement means that these models have not been used to model the UK's land-use change SOC flux. Many process-based models require input data relating to the amount of leaf litter input for each land-use, its carbon and nitrogen contents, a monthly or sometimes daily temperature record, and information on soil texture and nitrogen deposition rates [*Peltoniemi et al.*, 2007].

[40] The results presented here help us to assess how changes in SOC as a result of land-use change have contributed to the UK's total GHG emissions. The UK's current industrial emissions are reported to be approximately 150 Tg C/yr [*Bellamy et al.*, 2005; *Ciais et al.*, 2009]. Although reference to Figure 4 shows that the carbon sequestered by land-use change was not a linear change in carbon stocks over the 82 year time period; if this was the case it would represent an increase in SOC stocks of 1.92 Tg C/yr. This suggests that on average, over the entire period, land-use change impacts on SOC have not contributed to UK emissions, and that land-use changes have in-fact sequestered carbon from the atmosphere. As discussed earlier however, assessing the contribution over such a large number of years does not reveal the extent of the contribution of some large yearly fluxes. The loss of 12.3 Tg C in 1942 represents greater than 8% of the current UK's industrial emissions. This figure bears much more relevance to our actions in current times, indicating that such land-use changes now could have severe consequences in the context of growing international pressure to reduce GHG emissions over a short time period. This loss, however, represented only 0.82% of the UK's estimated SOC stock at that time, and is therefore significantly smaller than the 10% change in global SOC stocks that would be needed to represent 30 years of global anthropogenic CO_2 emissions [*Kirschbaum*, 2000]. The sink of 4.31 Tg C in 1993 represents 2.87% of the current UK's industrial emissions. This indicates that although similar land-uses changes in the future could be made to offset some of the industrial emissions, many other changes besides land-use change must also be implemented if the targets of 34% reduced CO_2 emissions by 2020 are to be met.

[41] The results of this study suggest that the SOC sink provided over this period by changes in UK land-use have compensated for the quoted losses [*Bellamy et al.*, 2005; *Smith et al.*, 2007a] resulting from climate change, and offset some of the losses caused by agricultural land management change under continuous land-use. These findings do not contradict those of *Bellamy et al.* [2005], but show that we should not assume that SOC emissions to the atmosphere have increased. Instead we must consider all forms of land-use and land-management change, and include all sequestration and emissions in calculation of total SOC change. The effects of increased productivity under a changing climate, and potential for improved agricultural technology on counteracting a tendency for climate change to speed decomposition, and thereby enhance SOC loss was also examined by *Smith et al.* [2005], showing that increasing SOC sinks are possible under a changing climate.

[42] This research also allows us to assess the extent of the UK's carbon emissions in relation to other countries, and the land-use changes that they have made. The loss of 12.3 Tg C in 1942 is three to four times greater than the loss of SOC predicted from SOC models looking at the conversion of forest land to arable land in Brazil [*Maia et al.*, 2009]. It is estimated that throughout the period 1985–2002 3.74 Tg C/yr were lost from the soil in Brazil [*Maia et al.*, 2009], though the largest losses from deforestation are in the lost vegetation. Although the loss estimated in this study for the year 1942 only occurred for one year, and is not a continual situation in the UK, it emphasizes the extent of the losses possible from UK land-use change, when the levels emitted from Brazil's rain forest deforestation are of great concern on a global scale.

[43] Caution needs to be taken when assessing the results from all model outputs, as *Wutzler and Reichstein* [2007] argue that using an observed carbon stock in a soil carbon model to represent equilibrium is incorrect because it is based on the assumption that the soil sample represents a soil at equilibrium. In this study we recognize that the SOC concentrations ascribed to land-uses may not be representative of soils at equilibrium, and that climate change and land-management change means that such equilibrium may never be reached. The SOC concentrations used in this model do though represent typical SOC concentrations for these land-uses, and the scale of the sample size, and the use of such a large database should be considered as a more accurate model than those using much smaller databases on which to base their typical land-use SOC stocks [e.g., *Maia et al.*, 2009].

[44] The results show that the use of a regional database or a country specific database when attempting to estimate SOC fluxes on a scale as great as the UK will provide inaccurate results (Figure 8). When predicting fluxes for the UK the amalgamated database was considered the best source, as it is expected that the number of samples from different soil types will be representative of the area of these soil types in the UK. This is in comparison to a regional

database where a large area of highly organic or mineral soil may skew the SOC values. This is represented by use of the Wallington database for predicting the UK SOC flux, where a large area of forestry exists on organic soils [*Bell and Worrall*, 2009]. In the case of the UK however, the approach used in this study is deemed more than satisfactory, and could not be improved given the land-use change information available.

[45] Although the SOC transition times used in this modeling study are only estimates, it is believed that these are the most accurate available, having been estimated using evidence from over 20 previous studies for both SOC losses and gains. In an ideal world transition times would be measured following land-use change, however the slow rate at which SOC adjusts to this change makes long-term trials difficult to conduct, and is the reason why such information is lacking [*Ogle et al.*, 2009].

[46] When interpreting the results it has been assumed throughout that any losses or gains in SOC are the result of either C sequestration from the atmosphere or a release of C to the atmosphere. One final point of caution is that some of this SOC loss following a land-use transition may not in-fact have been emitted to the atmosphere, and could actually have been lost to surface waters as dissolved organic carbon (DOC), dissolved CO_2 or leached into deeper soil layers. Although there is no evidence for increased dissolved CO_2 losses over time from the UK [*Worrall et al.*, 2007] there is extensive evidence that DOC flux from the UK has increased. *Worrall et al.* [2009] has shown that DOC flux from the UK has increased from 0.8 Tg C/yr in 1975 to a peak of 1.9 Tg C/yr in 2003. Although the extent to which this is likely to have occurred is currently unknown, it implies that any of the quoted figures relating to carbon sequestration over this period should be adjusted upwards (to a larger C sink), as losses to the atmosphere may not be as great as initially thought.

[47] Although there are still many uncertainties involved in modeling the impact of past land-use on the UK's SOC stock, and SOC fluxes to and from the atmosphere, this study does reveal the order of magnitude to which land-use is affecting total atmospheric CO_2 concentrations, and therefore provides an insight into the importance of our future land-use change decisions.

[48] An evaluation of the model with real measured data would validate the model; however the nature of SOC concentration change and the long transition times means that lengthy field trials will be required. To validate the models use in all areas of the UK an extensive campaign of land-use change and SOC flux measurements should be implemented.

[49] **Acknowledgments.** Research funded by a grant from The National Trust. Soil Organic Carbon values obtained from a database supplied by DEFRA. PS is a Royal Society-Wolfson Research Merit Award holder. Thanks to the Wallington tenant farmers, Wimpole farm staff and The Forestry Commission for access to their land and the provision of land-use and land-use history information. Thanks also to Newcastle University for provision of soil sampling equipment.

References

Adger, W. N., and S. Subak (1996), Estimating above-ground carbon fluxes from UK agricultural land, *Geogr. J.*, *162*(2), 191–204, doi:10.2307/3059876.

Adger, W. N., K. Brown, R. Sheil, and M. C. Whitby (1992), Carbon dynamics of land use in Great Britain, *J. Environ. Manage.*, *36*, 117–133, doi:10.1016/S0301-4797(05)80139-2.

Andress, D. (2002), Soil carbon changes for bioenergy crops, contract 2F-00921, Argonne Natl. Lab., U.S. Dep. of Energy, Lemont, Ill.

Bell, M. J., and F. Worrall (2009), Estimating a region's soil organic carbon baseline: The undervalued role of land-management, *Geoderma*, *152*, 74–84, doi:10.1016/j.geoderma.2009.05.020.

Bellamy, P. H., P. J. Loveland, R. I. Bradley, R. M. Lark, and G. J. D. Kirk (2005), Carbon losses from all soils across England and Wales 1978–2003, *Nature*, *437*, 245–248, doi:10.1038/nature04038.

Black, H. I. J., et al. (2002), MASQ: Monitoring and assessing soil quality in Great Britain. Countryside Survey module 6: Soils and pollution, *Rep. E1-063/TR*, Cent. for Ecol. and Hydrol., Environ. Agency, Almondsbury, U. K.

Bonde, T. A., B. T. Christensen, and C. C. Cerri (1992), Dynamics of soil organic matter as reflected by natural ^{13}C abundance in particle size fractions of forested and cultivated oxisols, *Soil Biol. Biochem.*, *24*, 275–277, doi:10.1016/0038-0717(92)90230-U.

Bradley, R. I., R. Milne, J. Bell, A. Lilly, C. Jordan, and A. Higgins (2005), A soil carbon and land use database for the United Kingdom, *Soil Use Manage.*, *21*, 363–369, doi:10.1079/SUM2005351.

Cerri, C. E. P., et al. (2007), Simulating SOC changes in 11 land use change chronosequences from the Brazilian Amazon with RothC and Century models, *Agric. Ecosyst. Environ.*, *122*, 46–57, doi:10.1016/j.agee.2007.01.007.

Chambers, B. J., N. R. Critchley, S. C. Rose, A. Bhogal, and D. J. Hodkinson (1998), Soil nutrient status and botanical composition of grasslands in the Dartmoor ESA, project BD1429 report to Ministry of Agriculture, Fisheries and Food, ADAS Group, Gleadthorpe, U. K.

Cheng, H. H., and J. M. Kimble (2001), Characterization of soil organic carbon pools, in *Assessment Methods For Soil Carbon*, edited by R. Lal et al., pp. 117–129, Lewis, London.

Ciais, P., et al. (2009), The European carbon balance. Part 2: Croplands, *Global Change Biol.*, *16*, 1409–1428, doi:10.1111/j.1365-2486.2009.02055.x.

Coleman, K., D. S. Jenkinson, G. J. Crocker, P. R. Grace, J. Klir, M. Korschens, P. R. Poulton, and D. D. Richter (1997), Simulating trends in soil organic carbon in long-term experiments using RothC-26.3, *Geoderma*, *81*, 29–44, doi:10.1016/S0016-7061(97)00079-7.

Department for Environment, Food and Rural Affairs (2001–2008), *Agriculture in the United Kingdom*, Her Majesty's Stationary Office, London.

Easter, M., et al. (2007), The GE FSOC soil carbon modeling system: A tool for conducting regional-scale soil carbon inventories and assessing the impacts of land change on soil carbon, *Agric. Ecosyst. Environ.*, *122*, 13–25.

Falloon, P. (2002), Summary of soil and land use data for DEFRA CC02421, suggested improvements for final dataset and suggested modelling strategy, *Rep. CC02421*, Dep. of Environ., Food and Rural Affairs, London.

Falloon, P. (2003), Preliminary 1 km Soil C modelling outputs for Defra CC02421—Discussion report, *Rep. CC02421*, Dep. of Environ., Food and Rural Affairs, London.

Falloon, P., D. Powlson, and P. Smith (2004), Managing field margins for biodiversity and carbon sequestration: A Great Britain Case Study, *Soil Use Manage.*, *20*, 240–247, doi:10.1079/SUM2004236.

Falloon, P., P. Smith, R. I. Bradley, R. Milne, R. Tomlinson, D. Viner, M. Livermore, and T. Brown (2006), RothCUK—A dynamic modelling system for estimating changes in soil C from mineral soils at 1km resolution in the UK, *Soil Use Manage.*, *22*, 274–288, doi:10.1111/j.1475-2743.2006.00028.x.

Forestry Commission (2007), Forestry facts and figures 2007: A summary of statistics about woodland and forestry, *Rep. FCFS207/FC-GB(CLM)/ALDR-3K/SEP07*, The Forestry Commission, Edinburgh, U. K.

Grogan, P., and R. Matthews (2001), Review of the potential for soil carbon sequestration under bioenergy crops in the U.K. scientific report, report on contract NF0418, Minist. of Agric., Fish. and Food, Cranfield Univ., Silsoe, U. K.

Guo, L. B., and R. M. Gifford (2002), Soil carbon stocks and land use change: A meta analysis, *Global Change Biol.*, *8*, 345–360, doi:10.1046/j.1354-1013.2002.00486.x.

Haines-Young, R. H., et al. (2000), Accounting for nature: Assessing habitats in the UK countryside, CS2000 report, Cent. for Ecol. and Hydrol., Dep. of the Environ., Transp. and the Reg., London.

Heath, L. S., R. A. Birdsey, and D. W. Williams (2002), Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001, *Environ. Pollut.*, *116*, 373–380, doi:10.1016/S0269-7491(01)00213-5.

Holderness, B. A. (1985), *British Agriculture Since 1945*, Manchester Univ. Press, Manchester, U. K.

Houghton, R. A., and J. L. Hackler (2000), Changes in terrestrial carbon storage in the United States. 1: The roles of agriculture and forestry, *Glob. Ecol. Biogeogr.*, *9*, 125–144, doi:10.1046/j.1365-2699.2000.00166.x.

Howard, D. M., P. J. A. Howard, and D. C. Howard (1995), A Markov model projection of soil organic carbon stores following land use changes, *J. Environ. Manage.*, *45*, 287–302, doi:10.1006/jema.1995.0076.

Kaonga, M. L., and K. Coleman (2008), Modelling soil organic carbon turnover in improved fallows in eastern Zambia using the RothC-26.3 model, *For. Ecol. Manage.*, *256*, 1160–1166, doi:10.1016/j.foreco.2008.06.017.

Kimble, J. M., R. B. Grossman, and S. E. Samson-Liebig (2001), Methodology for sampling and preparation for soil carbon determinations, in *Assessment Methods for Soil Carbon*, edited by R. Lal et al., pp. 15–29, Lewis, London.

King, J. A., R. I. Bradley, R. Harrison, and A. D. Carter (2004), Carbon sequestration and saving potential associated with changes to the management of agricultural soils in England, *Soil Use Manage.*, *20*, 394–402, doi:10.1079/SUM2004270.

Kirschbaum, M. U. F. (2000), Will changes in soil organic carbon act as a positive or negative feedback on global warming?, *Biogeochemistry*, *48*, 21–51, doi:10.1023/A:1006238902976.

Krishnan, P., G. Bourgeon, D. Lo Seen, K. M. Nair, R. Prasanna, S. Srinivas, G. Muthusankar, L. Dufy, and B. R. Ramesh (2007), Organic carbon stock map for soils of Southern India: A multifactorial approach, *Curr. Sci.*, *93*(5), 706–710.

Jenkinson, D. S., P. B. S. Hart, J. H. Rayner, and L. C. Parry (1987), Modelling the turnover of organic matter in long-term experiments at Rothamstead, *INTECOL Bull.*, *15*, 1–8.

Lal, R. (2008), Soil carbon stocks under present and future climate with specific reference to European ecoregions, *Nutr. Cycling Agroecosyst.*, *81*, 113–127, doi:10.1007/s10705-007-9147-x.

Lee, H. C., B. A. McCarl, and D. Gillig (2005), The dynamic competitiveness of U.S. agricultural and forest carbon sequestration, *Can. J. Agric. Econ.*, *53*, 343–357, doi:10.1111/j.1744-7976.2005.00023.x.

Lilly, A., G. Hudson, J. S. Bell, A. J. Nolan, and W. Towers (2009), National Soil Inventory of Scotland (1978–1988): Site location, sampling and profile description protocols (NSIS_1), technical bulletin, draft version 1, Macaulay Land Use Res. Inst., Aberdeen, U. K.

Loveland, P. J. (1990), National Soil Inventory of England and Wales, in *Element Concentration Cadasters in Ecosystems*, edited by H. Lieth and B. Markert, pp. 73–80, VCH, New York.

Lubowski, R. N., A. J. Plantinga, and R. N. Stavins (2005), Land-use change and carbon sinks: Econometric estimation of the sequestration supply function, discussion paper 05-04, Resour. for the Future, Washington, D. C.

Ministry of Agriculture, Fisheries and Food (1926–2000), Agriculture in United Kingdom, Her Majesty's Stationary Off., London.

Maia, S. M. F., S. M. Ogle, C. E. P. Cerri, and C. C. Cerri (2009), Soil organic carbon stock change due to land use activity along the agricultural frontier of the Southwestern Amazon, Brazil, between 1970 and 2002, *Global Change Biol.*, *16*, 2775–2788, doi:10.1111/j.1365-2486.2009.02105.

Milne, R. (1999), Land use change and forestry: The 1999 greenhouse gas inventory for England, Wales and Northern Ireland, project report, Cent. for Ecol. and Hydrol., Edinburgh, U. K.

Milne, R., and T. A. Brown (1997), Carbon in the vegetation and soils of Great Britain, *J. Environ. Manage.*, *49*, 413–433, doi:10.1006/jema.1995.0118.

Milne, R., et al. (2007), UK emissions by sources and removals by sinks due to land use, land use change and forestry activities, edited by R. Milne and D. C. Mobbs, *Rep. C02272*, 278 pp., Natl. Environ. Res. Counc. Cent. for Ecol. and Hydrol., Edinburgh, U. K.

Motavalli, P. P., H. Discekici, and J. Kuhn (2000), The impact of land clearing and agricultural practices on soil organic C fractions and CO_2 efflux in the Northern Guam aquifer, *Agric. Ecosyst. Environ.*, *79*, 17–27, doi:10.1016/S0167-8809(99)00139-5.

Murty, D., M. U. F. Kirschbaum, R. E. Mcmurtrie, and H. Mcgilvray (2002), Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature, *Global Change Biol.*, *8*, 105–123, doi:10.1046/j.1354-1013.2001.00459.x.

Nieto, O. M., J. Castro, E. Fernandez, and P. Smith (2010), Simulation of soil organic carbon stocks in a Mediterranean olive grove under different soil-management systems using the RothC model, *Soil Use Manage.*, *26*, 118–125, doi:10.1111/j.1475-2743.2010.00265.x.

Ogle, S. M., F. J. Breidt, M. Easter, S. Williams, K. Killian, and K. Paustian (2009), Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model, *Global Change Biol.*, *16*, 810–822, doi:10.1111/j.1365-2486.2009.01951.x.

Ostle, N. J., P. E. Levy, C. D. Evans, and P. Smith (2009), UK land use and soil carbon sequestration, *Land Use Policy*, *26*, S274–S283, doi:10.1016/j.landusepol.2009.08.006.

Peltoniemi, M., et al. (2007), Models in country scale carbon accounting of forest soils, *Silva Fenn.*, *41*, 575–602.

Post, W. M., and K. C. Kwon (2000), Soil carbon sequestration and land-use change: Processes and potential, *Global Change Biol.*, *6*, 317–327, doi:10.1046/j.1365-2486.2000.00308.x.

Poulton, P. R., E. Pye, P. R. Hargreaves, and D. S. Jenkinson (2003), Accumulation of carbon and nitrogen by old arable land reverting to woodland, *Global Change Biol.*, *9*, 942–955, doi:10.1046/j.1365-2486.2003.00633.x.

Powers, J. S. (2004), Changes in soil carbon and nitrogen after contrasting land-use transitions in northeastern Costa Rica, *Biomed. Life Sci.*, *7*, 134–146.

Pumpanen, J., H. I. Ivesniemi, and P. Hari (2003), A process-based model for predicting soil carbon dioxide efflux and concentration, *Soil Sci. Soc. Am. J.*, *67*, 402–413, doi:10.2136/sssaj2003.0402.

Schlesinger, W. H. (1986), Changes in soil carbon storage and associated properties with disturbance and recovery, in *The Changing Carbon Cycle: A Global Analysis*, edited by J. R. Trabalka and D. E. Reichle, pp. 194–220, Springer-Verlag, London.

Schulp, J. E., G. J. Nabuurs, and P. H. Verburg (2008), Future carbon sequestration in Europe—Effects of land-use change, *Agric. Ecosyst. Environ.*, *127*, 251–264, doi:10.1016/j.agee.2008.04.010.

Schwartz, D., and M. Namri (2002), Mapping the total organic carbon in the soils of the Congo, *Global Planet. Change*, *33*, 77–93, doi:10.1016/S0921-8181(02)00063-2.

Scott, N. A., K. R. Tate, D. J. Giltrap, S. Tattersall, R. H. Wilde, P. F. L. Newsome, and M. R. Davis (2002), Monitoring land-use change effects on soil carbon in New Zealand: Quantifying baseline soil carbon stocks, *Environ. Pollut.*, *116*, S167–S186, doi:10.1016/S0269-7491(01)00249-4.

Smith, J. U., P. Smith, M. Wattenbach, S. Zaehle, R. Hiederer, R. J. A. Jones, L. Montanarella, M. D. A. Rounsevell, I. Reginster, and F. Ewert (2005), Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080, *Global Change Biol.*, *11*, 2141–2152, doi:10.1111/j.1365-2486.2005.001075.x.

Smith, P. (2004), Soils as carbon sinks: The global context, *Soil Use Manage.*, *20*, 212–218, doi:10.1079/SUM2004233.

Smith, P., D. S. Powlson, M. J. Glendining, and J. U. Smith (1997), Potential for carbon sequestration in European soils: Preliminary estimates for five scenarios using results from long-term experiments, *Global Change Biol.*, *3*, 67–79, doi:10.1046/j.1365-2486.1997.00055.x.

Smith, P., et al. (2007a), Climate change cannot be entirely responsible for soil carbon loss observed in England and Wales, 1978–2003, *Global Change Biol.*, *13*, 2605–2609, doi:10.1111/j.1365-2486.2007.01458.x.

Smith, P., et al. (2007b), ECOSSE: Estimating carbon in organic soils—Sequestration and emissions, final report, Scott. Exec. Environ. and Rural Aff. Dep., Edinburgh, U. K. [Available at http://www.scotland.gov.uk/Publications/2007/03/16170508/0.]

Smith, P., A. Bhogal, P. Edgington, H. Black, A. Lilly, D. Barraclough, F. Worrall, J. Hillier, and G. Merrington (2010), Consequences of feasible future agricultural land-use change on soil organic carbon stocks and greenhouse gas emissions in Great Britain, *Soil Use Manage.*, *26*, 381–398, doi:10.1111/j.1475-2743.2010.00283.x.

Su, Z.-Y., Y.-M. Xiong, J.-Y. Zhu, Y.-C. Ye, and M. Ye (2006), Soil organic carbon content and distribution in a small landscape of Dongguan, South China, *Pedosphere*, *16*(1), 10–17, doi:10.1016/S1002-0160(06)60020-9.

Tomlinson, R. W., and R. M. Milne (2006), Soil carbon stocks and land cover in Northern Ireland from 1939 to 2000, *Appl. Geogr.*, *26*, 18–39, doi:10.1016/j.apgeog.2005.10.001.

U.S. Environmental Protection Agency (2008), Climate leaders greenhouse gas inventory protocol—Offset project methodology for project type: Reforestation/afforestation, version 1.2, Clim. Change Div., Off. of Atmos. Programs, Washington, D. C.

Veldkamp, E. (1994), Organic-carbon turnover in three tropical soils under pasture after deforestation, *Soil Sci. Soc. Am. J.*, *58*, 175–180, doi:10.2136/sssaj1994.03615995005800010025x.

Webb, J., P. J. Loveland, B. J. Chambers, R. Mitchell, and T. Garwood (2001), The impact of modern farming practices on soil fertility and quality in England and Wales, *J. Agric. Sci.*, *137*, 127–138, doi:10.1017/S0021859601001290.

West, T. O., G. Marland, A. W. King, W. M. Post, A. K. Jain, and K. Andrasko (2004), Carbon management response curves: Estimates of temporal soil carbon dynamics, *J. Environ. Manage.*, *33*, 507–518.

Woomer, P. L., N. K. Karanja, and E. W. Murage (2001), Estimating total system carbon in smallhold farming systems of the E. African highlands, in *Assessment Methods for Soil Carbon*, edited by R. Lal et al., pp. 147–164, Lewis, London.

Worrall, F., T. Guilbert, and T. Besien (2007), The flux of carbon from rivers: The case for flux from England and Wales, *Biogeochemistry*, *86*, 63–75, doi:10.1007/s10533-007-9145-8.

Worrall, F., T. P. Burt, N. J. K. Howden, and M. J. Whelan (2009), Fluvial flux of nitrogen from Great Britain 1974–2005 in the context of the terrestrial nitrogen budget of Great Britain, *Global Biogeochem. Cycles*, *23*, GB3017, doi:10.1029/2008GB003351.

Wutzler, T., and M. Reichstein (2007), Soils apart from equilibrium—Consequences for soil carbon balance modelling, *Biogeosciences*, *4*, 125–136, doi:10.5194/bg-4-125-2007.

Yang, Y., J. Fang, Y. Tang, C. Ji, C. Zheng, J. He, and B. Zhu (2008), Storage, patterns and controls of soil organic carbon in the Tibetan grasslands, *Global Change Biol.*, *14*, 1592–1599, doi:10.1111/j.1365-2486.2008.01591.x.

Zaehle, S., et al. (2007), Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990–2100, *Ecosystems*, *10*, 380–401, doi:10.1007/s10021-007-9028-9.

Zak, D. R., D. F. Grigal, S. Gleeson, and D. Tilman (1990), Carbon and nitrogen cycling during old-field succession: Constraints on plant and microbial biomass, *Biogeochemistry*, *11*, 111–129.

D. Barraclough, Environment Agency, Rio House, Waterside Drive, Aztec W., Almondsbury, Bristol BS32 4UD, UK.

M. J. Bell and P. Smith, Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, 23 St Machar Dr., Aberdeen AB24 3UU, UK. (m.j.bell@abdn.ac.uk)

A. Bhogal, ADAS Limited, Gleadthorpe Research Centre, Meden Vale, Mansfield NG20 9PF, UK.

H. Black and A. Lilly, Macaulay Institute, Craigiebuckler, Aberdeen AB15 8QH, UK.

G. Merrington, WCA Environment Limited, Brunel House, Volunteer Way, Farringdon SN7 7YR, UK.

F. Worrall, Department of Earth Sciences, Science Laboratories, South Road, Durham DH1 3LE, UK.