Journal of Environmental Quality, Vol. 47, Issue 4, 2018, pp. 695-703
DOI: 10.2134/jeq2017.08.0310

Estimating changes in soil organic carbon with climatic using CENTURY in England and Wales

Ruben Sakrabani and John Hollis
Cranfield Soil and Agrifood Institute, School of Water, Energy and Environment, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK. Tel: +44 (0) 1234 750111 ext 2710
r.sakrabani@cranfield.ac.uk

Abstract

Soil organic carbon (SOC) dynamics are complex and models have been developed for predicting future changes, validated using only individual site data. In this study, we used the CENTURY model to predict changes in SOC between 1978 and 2000 using input weather data for 1978 – 2000 from the UK Meteorological Office and soil property input data derived from the National Soil Inventory (NSI). The predicted changes in SOC from the model simulation were validated using the re-sampled NSI data for the period 1994-2000. The modelling results indicate that CENTURY gave unacceptable predictions of change for three specific soil types. When these were omitted from the accuracy assessment, model predictions were statistically acceptable for all ecosystem types with Model Efficiencies (ME) decreasing in the order: Semi-natural grassland (ME=0.63) > Woodland (ME=0.27) > Arable (ME=0.08) > Managed grassland (ME=0.02). When compared to the overall measured rates of change, CENTURY correctly predicted the direction but under-predicted its magnitude of change. Once this utility was established, CENTURY was used to predict national-level climate change-induced changes in SOC based on the UKCIP02 scenarios for the 2020's, 2050's and 2080's, each of which comprise four emissions scenarios. The modelling predictions suggest that the predicted changes between scenarios were small. However within that, the greatest decrease (of 1.54% SOC) will be in semi-natural grassland under the 'High emissions' scenario. The future predicted pattern of change in SOC is greater in managed grassland (reduction of 0.27 – 0.39% SOC) than arable land (reduction of 0.03 – 0.05% SOC).

Keywords: soil organic matter; climate change; CENTURY; soil organic fractions

Published by American Society of Agronomy / Crop Science Society of America.
This is the Author Accepted Manuscript.
Please refer to any applicable publisher terms of use.

1. Introduction

Soil forms an important carbon stock in nature but the stocks are dynamic and changes in land-use, land management and climate can all have significant impacts. Climate change can influence the stock of soil organic matter in two ways: by changing plant growth, thus altering the annual return of plant debris to the soil; and by changing the rate at which this input decays in or on the soil (Jenkinson et al., 1991). One of the effects of global warming will be to accelerate the decomposition of soil organic matter, thereby releasing CO_2 to the atmosphere, which will further enhance the warming trend. More than twice as much carbon is held in the top metre of soil as in the atmosphere (Post et al., 1982; Batjes, 1996) and one of the current debates on the impact of climate change is whether soils will act as an overall 'sink' or 'source' of carbon in the future.

Recent analysis of data from the National Soil Inventory (NSI) of England and Wales, a unique national dataset (containing over 6000 samples) quantifying changes in topsoil (15 cm depth) organic carbon under arable, grassland, semi-natural vegetation and woodland (deciduous and coniferous) between the periods 1978-1983 and 1994-2003 indicated a consistent pattern of reduction in soil organic carbon content across all soil types and ecosystems (Bellamy et al., 2005). Moreover, there was an overall trend showing that the relative rate of loss increased with initial soil carbon content. The implication is that, in England and Wales at least, soils could be acting as an overall source of atmospheric carbon rather than a sink.

Soil organic carbon (SOC) models, such as CENTURY and RothC, can be used to simulate soil organic matter dynamics and predict changes in SOC under different management and climate scenarios (Falloon and Smith, 2002). Moreover, with SOC changes now an integral part of climate change policy, SOC models have become an important predictive tool for both scientists and policy makers (Campbell and Paustian, 2015). Easter et al. (2007) reported the use of the Global Environmental Facility Soil Organic Carbon (GEFSOC) model which simulated SOC dynamics in the Great Plains/Rocky Mountain ecotone in the state of Montana, in the Northern United States. GEFSOC is the framework for modelling SOC using a GIS approach and integrates CENTURY and RothC, together with the IPCC empirical model. The IPCC method predicts relatively large soil C stock changes for conversion from conventional to no-till systems in dry, temperate regions (+10% over 20 years) relative to CENTURY (+4% over 20 years) and RothC (approximately no change). The difference in stock change estimates between CENTURY and RothC, in this case, is expected, as CENTURY specifically simulates differences in tillage intensity and its impact on soil C whereas RothC does not. This shows that each model has its own limitations and that model outputs need to be interpreted accordingly.

Falloon and Smith (2002) report the use of RothC and CENTURY in isolation and in conjunction with each other to model SOC turnover in a Hungarian Long Term Experimental (LTE) site in comparison to locations in UK and Sweden. Model outputs differ depending on the type of model used. Based on the weight of evidence supporting decomposition rates predicted by both models, and C inputs estimated by CENTURY, it is difficult to determine which (and indeed, if) either

model is 'correct'. Most of the relationships underlying both models were derived from different datasets, and the complex nature of the differences between model structures, rate modifying factors and flows between pools renders making any concrete conclusion almost impossible.

Various soil carbon cycling models have been developed over the last twenty years (Smith et al., 1997; Campbell and Paustian, 2015) and most separate the SOC mass into various pools based on assumed turnover times as a way of dealing with stabilization of SOC dynamics (Sollins et al., 1996). Within one or more of the pools, the reaction dynamics can vary according to specific environmental drivers. However, the dynamics of soil organic carbon are complex and remain imperfectly understood. The problem with using the multi-pool models is that they can be difficult to parameterise and is something that we explored in detail in this paper. As a result, most have only been validated using individual site data and following careful calibration. The objective of this paper is to assess the utility of one of the more widely used carbon cycling models, CENTURY (Parton *et al.,* 1987), to predict the measured changes in soil organic carbon across England and Wales and to use this assessment to interpret results of its use with the UKCIP02 (United Kingdom Climate Impacts Programme 2002) scenarios for the 2020's, 2050's and 2080's.

2. Methods

2.1 The CENTURY model

The model used in the work reported here is CENTURY (Metherall et al, 1993; Parton et al, 1994) v. 5. The CENTURY model was selected because it has been

evaluated at the site scale for a range of agricultural ecosystems (Paustian *et al.*, 1992, Metherell *et al.*, 1995) and a limited number of, woodland ecosystems (Sandford *et al.*, 1991; Levy *et al.,* 2004) and fen (Chimner *et al.*, 2002), as well as in some regional applications (Paustian *et al.,* 1997). Version 5 of CENTURY was chosen because it has a graphical user interface that simplifies model input. Additional information regarding CENTURY 5 can be found in the Supplemental Material.

2.2 Selection of indicator soil series

In order to represent the range of soil types that occur under different ecosystems in England and Wales, a number of 'indicator' soil types were selected for modelling. Each selected soil type was most commonly represented in the ecosystem according to data from the NSI and gives a good representation of the range of soil types across England and Wales as summarised in Table 1.

2.3 Model Parameterisation

2.3.1 Derivation of soil physical and chemical input data

Soil parameter datasets used to drive CENTURY were obtained from the soil series profile datasets held within NSRI's (National Soil Resources Institute) Land Information System, LandIS (Hallett *et al.*, 1996). Mean values were used to characterise the mineral particle-size fractions of each soil horizon of the indicator soil types.

The mean values of topsoil organic carbon content and pH used in CENTURY were derived from the National Soil Inventory (McGrath & Loveland, 1992). This

comprises 5,692 sets of analysed values of soil chemical (organic carbon, pH, extractable heavy metals & nutrients etc.) and mineral particle-size properties from 15 cm deep topsoil samples taken at 5 km grid intersect points across England and Wales during the period from 1978 to 1983. The dataset provides a soil geochemical baseline for the late 1970s in England and Wales. In order to characterise changes over time, statistically valid subsets of the National Soil Inventory sites were re-sampled and analysed during 1994-95 (904 Arable sites), 1995-96 (780 Grassland sites) and 2002-2003 (598 Semi-natural grassland and woodland sites). In addition, because both organic carbon and pH are very dependent on land use, even within soil series, the data were further stratified into four land use categories: Arable, Managed Grassland, Semi-natural Grassland and Woodland.

The SOC was divided into three pools because of the different stability of the carbon encountered in the ecosystems that were modelled. Soil carbon does not exist in one pool, with the stability of the C corresponding to the origin of the material from which it was derived. For instance, if a woody material is present, the carbon associated with it is more stable than if it is of a plant or leaf origin. Hence the approach of Kelly et al. (1997) was used to divide the bulk SOC content (derived from the NSI) into three separate carbon pools: active, slow and passive. Splitting the SOC input data into three pools provides better prediction building on Kelly et al. (1997). The details of the different fractions used to divide the bulk SOC for arable, woodland and grassland are detailed in the Supplemental Material (Table S4).

Bulk density and soil water retention characteristics also depend, at least partly, on land use. The analytical data held in LandIS is insufficient to directly characterise all combinations of series and land use; therefore, values for individual soil horizon/land use combinations were estimated using pedotransfer functions (PTF) derived from analysis of the measured data held within LandIS (Thomasson and Carter, 1992, Simota and Mayr, 1996, Mayr and Jarvis, 1999). That is, the PTF were derived using multiple regression analysis of the measured data based on horizon organic carbon content, particle size fractions and, in the case of the water retention properties, bulk density, as the independent variables (Hollis *et al*, 1993). Data obtained using the PTF were input into the model only for the simulation layer, which is the topsoil at 15 cm depth. Further details of the PTF are provided in the Supplemental Material.

2.3.2 Derivation of weather data

Weather data comprising minimum temperature, maximum temperature and precipitation from 1978 to 2000—derived from the UKCIP 'Baseline' (1961-2000) 50-km × 50-km grid datasets produced by the Meteorological Office—were used to drive the model simulations for calibration purposes. As the model input soil parameters were based on mean measured values for ecosystem indicator soil types, and are thus not location-specific, the weather data used to drive the CENTURY simulations was derived from average parameter values for all the grids covering England and Wales.

Weather data to drive the model simulations of future climate change scenarios were derived from the UKCIP02 datasets for the 2020's (2011–2040), 2050's

(2041–2070) and 2080's (2071–2100) under four emissions scenarios (i.e. high, low, medium-high and medium-low; see Supplemental Tables S1 and S2 for details). The average parameter values for scenario-specific monthly weather data were derived from all grids covering England and Wales.

2.3.3 Derivation of management scenarios

The management scenarios for modelling SOC dynamics include arable (intensive and less intensive rotation involving sugar beet-cereal and oil seed rape-cereal respectively), grassland (temperate grass clover pasture), semi natural grassland (C3 grass species) and woodland (deciduous and coniferous). These options were chosen based on information provided by the Agriculture and Horticulture Development Board, which is a levy body for arable farmers in the UK. Additional information detailing the management scenarios is presented in the Supplemental Material. For arable ecosystems, sensitivity analysis showed that the end result of the modelled OC is very dependent on plant litter values that are returned to the soil. Initially therefore, default plant litter values based on the two different management scenarios were used as input for the calibration model runs. For the predictive model runs however, plant litter values based on those obtained at the end of the calibration run were used.

Sensitivity analyses on the CENTURY Forest model by Levy et al., (2004) found that the parameters controlling the allocation of assimilates between leaves, roots and stem are the most sensitive parameters influencing SOC turnover. Of these, the strongest partial correlation was with the carbon allocation fraction of fine roots and leaves for mature forests. In an attempt to improve the simulation results for

woodland therefore, this allocation fraction was based on advice from the UK Forest Research, using data held in their archives.

2.4 Model calibration

In order to ensure that model simulations used reasonable sets of input parameters, the model was run for 2000 years (spin up run) using a set of default or generic values related to management scenarios (as described in the Supplemental Material) and involving choices of crops, fertilization regime, tillage practices, and irrigation system if needed). The specific values are related to soil and climate parameters. The organic carbon fractions for the spin up run were apportioned according to Kelly et al. (1997). Following a similar approach to Smith et al. (2005), the 2000-year run was to ensure that the model was at equilibrium before the actual run was set up. The new organic carbon fraction values at the end of this spin up run were then used as inputs to the actual simulation runs. In addition, relevant drainage and anaerobicity factors for specific soil types were derived by a calibration exercise against measured organic carbon changes. The parameters were varied and the resulting simulated change in organic carbon content compared to the measured changes to identify the most effective combination. The calibrated CENTURY model was run using the UKCIP02 baseline climate data for 1978-2000 to predict topsoil organic carbon content for each selected indicator soil type/ecosystem combination (Table 1).

The first simulation run was the spin up run using 1978-2000 climatic conditions. The second simulation run was then carried out using the new organic carbon fractions derived from the spin up run. For the long-term (future) runs, the output

from the second run was used as a starting point, but with climatic data from 2030-2080.

Examination of the time series showing changes in the relative distribution of each organic carbon pool during the calibration run indicated that, because of their quick turnover rates, the litter and active SOC pools stabilise rapidly in all three ecosystems compared to the passive and slow pools after 2000 years.

2.5 Changing drainage and anaerobicity parameters

The DRAIN parameter is defined as the fraction of excess water lost by drainage from the topsoil layer and has a value varying between 0 and 1. During periods when the topsoil layer becomes waterlogged because of restricted drainage, the soil becomes sensitive for anaerobiosis (Metherall et al., 1993) and the model then applies a set of anaerobicity (ANREF) factors. The anaerobicity parameters are used to scale carbon decomposition rates between fully aerobic and fully anaerobic conditions, depending on the ratio of precipitation to potential evapotranspiration (P/PET). This relationship is based on observations by Franzluebbers et al., (2001) that the specific activities of soil microbial biomass were positively related to the ratio of precipitation (P) to potential evapotranspiration (PET) (P/PET). Parameterisation of both the DRAIN and ANREF values was initially based on soil type. For all soils that were considered to be free-draining, at least in their upper layers, a DRAIN value of 1 was used and the default values of ANREF1, 2 and 3 were used. For other soils such as slowly permeable, seasonally wet ones, those seasonally waterlogged by rising groundwater, and those waterlogged in their upper

layers for some or most of the year because of an excess of rainfall over evapotranspiration, the impact of different values was tested.

2.5 Statistical Analysis

To assess the reliability of model predictions, the model efficiency (ME) of prediction was used:

$$ME = 1\text{-}\frac{\sum_{i=1}^{n}(E_i\text{-}M_i)^2}{\sum_{i=1}^{n}(M_{\bar{x}}\text{-}M_i)^2}$$

where E_i is the ith estimated organic carbon content value, M_i is the ith measured organic carbon content value, and n is the number of data pairs consisting of E_i and M_i for that pressure head, $M_{\bar{x}}$ is the mean of all measured organic carbon content values.

Model efficiency values of 0 indicate that accepting the model predictions is no better than simply using a mean value of the observed data, whereas ME values of 1 indicate no errors of prediction. Values between 0 and 1 thus indicate a better prediction than when simply using a mean measured value and negative ME values indicate unacceptable prediction. Values of 0.6 or greater are considered to indicate good prediction (Loague and Green, 1991).

To assess the likely error associated with the predictions we used the root mean square error (RMSE) of prediction:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i\text{-}M_i)^2}{n}}$$

Finally, to assess the accuracy of prediction of the trend of change for indicator soil types covering each ecosystem, the percentage of data points in each ecosystem showing the correct trend (negative or positive) was calculated and compared with the trend of its mean measured and mean predicted changes.

3. Results and Discussion

3.1 Drainage and anaerobicity parameters

For Beccles and Dunkeswick series (Luvic Stagnosols), the model correctly predicts the measured direction of change (data not shown). For the Evesham series the model incorrectly predicts the measured direction of change and the DRAIN value that gives the best prediction of the measured value in 1995 is the same as that for the Beccles series. In addition, for the Dunkeswick soil series, predicted organic carbon end points do not consistently increase with decreasing drainage, as would be expected. The reason for this is not clear. The selection of a suitable DRAIN value for such soils is thus problematic and is likely to depend on local factors such as the effectiveness of field drainage systems, where present and soil structural conditions.

In contrast to these soil types, wet lowland heath podzols (subgroup 6.4* - Table 1) are the only soil type to show a measured increase in topsoil organic carbon. The measured data are all from the New Forest area of Hampshire and Dorset where the soils are associated with small areas of 'valley mire' ecosystems (Jarvis et al., 1984) and the waterlogged conditions are controlled principally by local hydro-topographic features rather than climatic factors. The only way that such changes could be simulated using CENTURY was to limit the drainage of excess water from

the upper soil layer and to use the anaerobicity parameters in the model to reduce decomposition rates due to anaerobic conditions. Calibration of these parameters has been used to successfully model carbon changes in two fen ecosystems in the USA (Chimner *et al.*, 2002).

Results of predictions using two different sets of ANREF values in combination with a DRAIN value of 0.31 are shown in Figure 1. The predicted 2003 SOC value in Box B (Figure 1), where the anaerobicity parameters are much lower than in Box A (Figure 1), most closely matches the measured 2003 value. It is thus clear that, using a combination of the DRAIN and ANREF parameters, CENTURY can be calibrated to predict organic carbon changes in such wet soils.

Based on this calibration exercise, a DRAIN value of 0.95 was allocated to all slowly permeable soils with perched water tables of variable duration under the arable and managed grassland ecosystems. It was estimated that all such soil ecosystem combinations would have field drainage installed, which would significantly reduce the amount of waterlogging in the topsoil layers. Under semi-natural ecosystems (woodland or grassland), such soils were allocated DRAIN values of 0.7 where they were classed as Stagnic Luvisols (7.11) and values of 0.6 where they were classed as Stagnic Cambisols (7.13). These values were based on the separate Wetness Class and drainable porosity for each soil type, which indicate that the former is more permeable in its upper layers and also wet within 40 cm depth for shorter periods than is the latter soil type.

3.2 Predictions of short-term (current) measured change

Changes in topsoil organic carbon content between the original sampling (1980) and the re-sampling (1995), together with the CENTURY model-predicted topsoil organic carbon contents for the re-sampling dates, are shown in Figures 2 and 3. The accuracy of these year-specific model predictions was statistically evaluated (Table 2A), and it was determined that CENTURY gave a good prediction of the measured changes in topsoil organic carbon content for the indicator soil types under Semi-natural grassland & heathland ecosystems (ME = 0.63, 100% correct prediction of the trend of change both positive and negative and a RMSE of prediction of 2.16 compared to a root mean measured change of 5.16 ± 3.37). For the indicator soil types under deciduous woodland, the model predictions were weak but still acceptable (ME = 0.28, 63% correct prediction of the trend of change, both positive and negative and a RMSE of prediction of 4.73 compared to a root mean measured change of 6.12 ± 5.44). For all other ecosystems, model predictions were unacceptable with negative ME values between -0.35 and -1.51 and RMSE values larger than the standard deviation of the root mean measured changes. CENTURY model predictions of the measured changes across all indicator soil types within all ecosystems were acceptable in that the trend (direction) of the predicted SOC change matched that of the measured change, though the absolute magnitude of the predicted change was less accurate (ME of 0.46, 62% correct prediction of the trend of change, both positive and negative and a RMSE of prediction of 2.31 compared to a root mean measured change of 3.34 ± 2.99) (Table 2A).

In order to identify possible reasons for the poor predictions in arable, managed grassland and woodland systems, the predictions for individual indicator soil types

(Figures 2 and 3) were assessed to identify those giving the greatest errors. Firstly, all predictions that correctly simulated the trend in topsoil organic carbon change were taken as acceptable, regardless of the magnitude of the error. Secondly, predictions where the absolute difference between the measured and predicted magnitude of change was small (i.e., <20% of the original measured organic carbon content) were deemed acceptable—regardless of whether the predicted direction of change was correct. The results of this assessment are summarized in Table 2B.

The Beccles, Brickfield, Clifton, Cegin, Dunkeswick, Evesham, Salop, Wickham, Wilcocks, 7.11, and 7.13 soils are all slowly permeable with seasonally perched waterlogging of varying duration. Under arable and managed grassland they have field drainage systems installed to alleviate such waterlogging in their upper layers, but this is unlikely to be the case for woodland ecosystems. As discussed in section 3.1, calibrating the DRAIN & ANREF parameters for such soils is problematic and it is likely that the unacceptable predictions for the Evesham, Wickham, Wilcocks, and 7.11 indicator soils mean that the calibrated values used in the model do not reflect their local drainage conditions. For these soils it is likely that organic carbon dynamics are controlled largely by the soil water regime and associated redox potentials. CENTURY clearly has problems in simulating such organic carbon dynamics, giving a significant under-prediction of the measured losses and, in the case of the Wilcocks soil, even predicting an increase in organic carbon (see Figure 3).

According to Campbell and Paustian (2015), until SOM saturation kinetics can be appropriately implemented in SOM models, the potential for bias in models based

on kinetically-defined SOM pools should be recognized in SOM model applications aimed towards increasing SOM storage. High OM soils in systems with high OM inputs are vulnerable to overestimation of SOM storage and accumulation, when simulated using conventional first-order decay SOM models.

The Newport and 5.5* subgroup soils are both dominated by loamy sand or sand textures and have weak or little topsoil structure. Such soils are used as indicator soil types in arable, deciduous and coniferous woodland ecosystems and CENTURY clearly has a problem simulating organic carbon dynamics in these soils, giving unacceptable predictions in arable and coniferous woodland, whilst under deciduous woodland, although the change trend is correctly predicted, it gives the largest absolute predictive error as a percentage of the original carbon content of all indicator soil types in any ecosystem. More work is needed to resolve this problem.

Indicator Soil types in the 6.31 subgroup are Haplic Podzols which, under non-agricultural ecosystems, are very acid and characterized by the formation of organo-sesquioxodic complexes in the upper layers which leach downwards through the profile. There are only two such indicator soil types in the analysis, one under semi-natural grass or heath land and the other under coniferous woodland. In both ecosystems, CENTURY predicts a significant decrease in topsoil organic carbon content over the short term simulation period whereas the measured data shows a large contrast between the two of them, with a significant decrease only for the semi-natural grass or heath land soil and a significant increase in the coniferous woodland ecosystem. We are not certain why there is such a contrast between the two sets of measured data. However, the most likely explanation is that it results

from local woodland factors such as under-storey management, species composition of stands or stage of woodland development giving very different organic carbon dynamics to those simulated for coniferous woodland. These problems do not arise with the soil type under semi-natural grass or heath ecosystems.

Having identified the indicator soil types and all ecosystem combinations giving unacceptable predictions, these were then eliminated from the dataset and the statistical analysis repeated with the remaining soil types. The results are shown in Table 2B and show that elimination of combinations with unacceptable prediction of measured change resulted in acceptable, though weak ME values for arable, managed grassland, and both woodland ecosystems whilst the ME value for the semi-natural grass and heath land ecosystem was unchanged at 0.63. For all ecosystems, the revised analysis has a ME of 0.47 and a RMSE of 2.48 (Table 2B), compared to a standard deviation of the root mean measured change of 3.70 ± 3.28. This indicates that the accuracy of prediction of the measured short-term change in organic carbon content, though not strong, was acceptable.

In order to compare the predicted changes with the changes reported by Bellamy et al. (2005), the predicted data for each indicator soil type in the three ecosystems were converted to mean annual changes in topsoil organic carbon over the period between sampling measurements. The relationship between these values and the initial measured organic carbon content is shown below:

$$\hat{y} = 0.0396 - 0.0103x$$

where $\hat{y}$ = predicted annual rate of change in topsoil organic carbon (% yr^{-1}), and x = initial topsoil organic carbon (%).

Table 3 summarises the linear regression equations for similar relationships derived by Bellamy et al. (2005) and from the measured data for each of the indicator soil types. Using these regression equations to calculate the mean annual rate of change, based on the mean initial organic carbon percentage of all the indicator soil types gives values of -0.022 for the predicted data, -0.054 for the measured data and -0.046 for the data from Bellamy et al. (2005), which represents the value derived from a much larger range of measured NSI data. The overall trend is that the rate of reduction increases with increasing initial mean organic carbon content, and is similar for both the CENTURY simulated data and the measured data. This further substantiates the findings from analysis of individual ecosystems and suggests that the CENTURY model can be applied to predict overall regional changes in topsoil organic carbon content for areas dominated by arable, managed grassland and semi-natural grass or heath land ecosystems but may underestimate the magnitude of such changes.

3.3 Predictions of long-term (future) change

Predictions of future changes in soil organic carbon content were made using the calibrated CENTURY model with organic carbon input data based on the measured re-sampled NSI data for indicator soil types and driven by the UKCIP02 scenario weather datasets for the 2020's (years 2011–2040), 2050's (years 2041–2070) and 2080's (years 2071–2100). For future predictions, weather data was available only as average monthly values. Thus, for each scenario, weather datasets for the relevant periods were constructed using the average monthly data for those periods.

Results of running the calibrated CENTURY model with each of the climate change scenario datasets are summarised in Table 4. Figure 4 shows that organic carbon in soils from the Panholes and Elmton soil series under future climatic continue to decline. This can be attributed to the free draining nature of these soils (Table 1) which promote a quick turn over of organic carbon. Oscillations in the modelled data (Figure 4) reflect carbon inputs in terms of stubble or other residues incorporated into the soil (shown as an increase in soil carbon) and the loss of carbon during crop growth (shown as a decrease in soil carbon). The magnitude of these oscillations varies with the different crop rotations.

CENTURY predicts that, on average, topsoil organic carbon contents under traditional UK arable systems are almost at equilibrium and may decrease in free draining soils (such as Panholes and Elmtom) under a 'medium high' emissions scenario. In contrast, under both relatively intensively managed grassland ecosystems and semi-natural grass or heath land ecosystems, topsoil organic carbon is predicted to decease—with the greatest decreases occurring in the latter ecosystem. In all cases, the greatest decrease in topsoil organic carbon content occurs under the High emissions scenario and there is very little difference between mean predicted changes for the Medium High, Medium Low and Low emissions scenarios. Under both managed grassland and semi-natural grass or heath land ecosystems, it is likely that the mean measured reductions in topsoil organic carbon will continue at the same rate well into the future and may even increase slightly. The only ecosystems where such changes are not likely to occur are those where soil waterlogging is maintained by local hydro-topographic conditions.

4. Conclusions

CENTURY has been shown to give the most acceptable simulation of measured short-term regional changes in topsoil organic carbon under semi-natural grass or heath land ecosystems followed by woodland ecosystems. The predictions were least acceptable for arable and managed grassland. Initial evaluation of the predictive accuracy of CENTURY using measured data from a range of indicator soil types five under different ecosystems indicated that the model had problems simulating short-term changes in topsoil organic carbon content for soil types dominated by loamy sand or sand textures, for free-draining Podzols and for slowly permeable, seasonally wet soils with either dense, massive clay subsoils or with climatically-induced humose to peaty topsoils. Eliminating such soils from the indicator soil types resulted in statistically acceptable predictions for all ecosystem types—especially for semi-natural grass or heath ecosystems. Bearing in mind these limitations, CENTURY tended to underestimate the overall magnitude of the change in SOC, but correctly predicted the overall trend (direction) of the measured SOC changes.

CENTURY simulations based on the UKCIP02 future climate scenarios show that, in arable, managed grassland and semi-natural grass or heath land ecosystems the greater the initial mean ecosystem organic carbon content, the greater the reduction in topsoil organic carbon content. Overall, the CENTURY model predictions between scenarios did not differ significantly. However, within this context, the greatest decrease (of 1.54% SOC) will be in semi-natural grassland under the 'High emissions' scenario. As well, the future predicted pattern of change in SOC is

greater in permanent grassland (reduction of 0.27–0.39% SOC) than arable land (reduction of 0.03–0.05% SOC).

Acknowledgements

The authors wish to acknowledge funding from the Department of Environment, Food and Rural Affairs (Defra) under contract CC0375. The authors wish to thank Ian Bradley for providing data on crop rotation, cultivation, harvest and related land management practices for the selected soil series. The authors also wish to specially thank Cindy Keough from Colorado State University for her continuous help and advice on the use of CENTURY. Help from Dr Lorna Brown (IGER) who provided data on atmospheric nitrogen deposition is also gratefully acknowledged. We also wish to acknowledge help from Pat Bellamy and Ann Holden for advice on statistical analysis of data and automation of the model runs, respectively.

Supplemental Material

Further information regarding (i) details of the CENTURY model, (ii) pedotransfer functions, (iii) descriptions of the management scenarios considered in CENTURY modelling, (iv) definitions of the four emissions scenarios, (v) temperature changes predicted for 2020s, 2050s and 2080s, (vi) explanation of soil types according to the World Reference Base and (vii) fractionation of bulk soil organic carbon into various pools needed in CENTURY modelling.

References

Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47:151-163.

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.

Campbell, E.E. and K. Paustian. 2015. Current developments in soil organic matter modeling and the expansion of model applications: a review. Environ. Res. Lett. 10: 123004.

Chimner, R.A., D.J. Coper, and W.J. Parton. 2002. Modeling carbon accumulation in Rocky Mountain fens. Wetlands. 22(1): 100-110.

Duchaufour, P., 1982. Pedology: pedogenesis and classification. London, 448 pp.

Easter M., K. Paustian, K. Killian, S. Williams, T. Feng, R. Al Adamat, N. H. Batjes, M. Bernoux, T. Bhattacharyya, C. Cerri, K. Coleman, P. Falloon, C. Feller, P. Gicheru, P. Kamoni, E. Milne, D.K. Pal, D.S. Powlson, Z. Rawajfih, M. Sessay and S. Wokabi. 2007. The GEFSOC soil carbon modelling system: A tool for conducting regional-scale soil carbon inventories and assessing the impacts of land use change on soil carbon. Agric. Ecosys. Environ. 122(1 Special Iss.): 13-25. ISSN 0167-8809

Falloon P. and P. Smith. 2002. Simulating SOC changes in long-term experiments with RothC and CENTURY: model evaluation for a regional scale application. Soil Use Manage. 18 (2): 101–111

Franzluebbers, A.J., R.L. Haney, C.W. Honetcutt, M.A. Arshad, H.H. Schomberg and F.M. Hons. 2001. Climatic influences on active fractions of soil organic matter. Soil Biol. Biochem. 33: 1103-1111.

Hallett, S.H., R.J.A. Jones and C.A. Keay. 1996. Environmental Information Systems Developments for Planning Sustainable Land Use. Int. J. Geogr. Info. Sys. 10(1): 47-64.

Hollis, J.M., S.H. Hallett and C.A. Keay. 1993. The development and application of an integrated database for modelling the environmental fate of pesticides. In: *Proceedings 1993 Brighton Crop Protection Conference - Weeds,* pp. 1355 - 1364.

Jarvis, M.G., R.H. Allen, S.J. Fordham, J. Hazelden, A.J. Moffat, R.G. Sturdy. 1984. Soils and their use in South East England. Bulletin 15, Soil Survey of Great Britain.

Jenkinson, D.S., D.E. Adams, A. Wild. 1991. Model estimates of CO_2 emissions from soil in response to global warming. Nature. 351: 304-306.

Kelly, R.H., W.J. Parton, G.J. Crocker, P.R. Grace, J. Klir, M. Körschens, P.R. Poulton and D.D. Richter. 1997. Simulating trends in soil organic carbon in long-term experiments using the Century model. Geoderma. 81: 75-90.

Levy, P.E., R. Wendler, M.V. Oijen, M.G.R. Cannell and P. Millard. 2004. The effects of nitrogen enrichment on the carbon sink in coniferous forests:

Uncertainty and sensitivity analysis of three ecosystem models. Water Air Soil Pollut. Focus. 4: 67-74.

Loague, K. and R.E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: overview and application. J. Contam. Hydrol. 7: 51-73.

Mayr, T.R. and N.J. Jarvis. 1999. Pedotransfer functions to estimate soil water retention parameters for a modified Brooks-Corey type model. Geoderma 91: 1-9.

McGrath, S.P. and P.J. Loveland. 1992. The soil geochemical atlas of England and Wales. Blackie Academic and Professional.

Metherell, A.K., L.A. Harding, C.V. Cole and W.J. Parton. 1993. CENTURY Soil organic matter model environment. Technical documentation. Agroecosystem version 4.0. Great Plains System Research Unit Technical Report No.4. UDSA-ARS, Fort Collins, Colorado, USA.

Metherell, A.K., C.A. Cambardella, W.J. Parton, G.A. Peterson, L.A. Harding and C.V. Cole. 1995. Simulation of soil organic matter dynamics in dryland wheat-fallow cropping systems. In: Soil Management and the Greenhouse Effect - Advances in Soil Science (eds. Lal R, Kimble J, Levine E, Stewart, BA), , CRC/Lewis Publishers, Boca Raton, FL, pp. 259-270.

Parton, W.J., D.S. Schimel, C.V. Cole and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51: 1173-1179.

Parton, W.J., D.S. Ojima, C.V. Cole and D.S. Schimel. 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Quantitative Modeling of Soil Forming Processes. SSSA Special Publication 39, Madison, WI, pp. 147-167.

Paustian, K., W.J. Parton and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen fertilized long term plots. Soil Sci. Soc. Am. J. 56 : 476-488.

Paustian, K., E. Levine, W.M. Post and I.M. Ryzhova. 1997. The use of models to integrate information and understanding of soil C at the regional scale. Geoderma. 79: 227-260.

Post, W.M., W.R. Emanuel, P.J. Zinke and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature. 289: 156-159.

Sandford, R.L. Jr., W.J. Parton, D.S. Ojima and D.J. Lodge. 1991. Hurricane effects on soil organic matter dynamics in forest production in Luquillo Experimental Forest, Puerto Rico: results of simulation modelling. Biotropica. 23: 364-372.

Simota, C. and T.R. Mayr. 1996. Predicting the soil water retention curve from readily-available data obtained during soil surveys. Int Agrophys. 10(3): 185-188.

Smith, P., J.U. Smith, D.S. Powlson, W.B. McGill, J.R.M. Arah, O.G. Chertov, K. Coleman, U. Franko, S. Frolking, D.S. Jenkinson, L.S. Jensen, R.H. Kelly, H. Klein-Gunnewiek, A.S. Komarov, C. Li, J.A.E. Molina, T. Mueller, W.J. Parton, J.H.M. Thornley and A.P. Whitmore. 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma. 81: 153-225.

Smith, J., Smith, P.,Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R. J. A., Montanarella, L., Rounsevell, M. D. A., Reginster, I., Ewert, F., 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080, Global Change Biol. 11: 2141–2152.

Sollins, P., P. Homann and B.A. Caldwell. 1996. Stabilization and destabilization of soil organic matter: mechanisms and controls. Geoderma. 74: 65-105.

Thomasson, A.J. and A.D. Carter. 1992. Current and future uses of the UK Soil Water Retention Dataset. In: Proceedings of the International Workshop on Indirect Methods for estimating the hydraulic properties of unsaturated soils. Riverside, California (eds. van Genuchten MTh, Leij FJ). pp. 355-358.

Table 1 Details of indicator soil types used for CENTURY 5 calibration

ARABLE			MANAGED GRASSLAND			SEMI-NATURAL GRASSLAND			CONIFEROUS WOODLAND			DECIDUOUS WOODLAND		
Soil Type†	**Soil Series**	**PET‡ (%)**	**Soil Type†**	**Soil Series**	**PET‡ (%)**	**Soil Type†**	**Soil sub-group**	**PET‡ (%)**	**Soil Type†**	**Soil sub-group**	**PET‡ (%)**	**Soil Type†**	**Soil sub-group**	**PET‡ (%)**
Calcaric Leptosols	Andover	2.2	Cambic & Luvic Stagnosols	Brickfield	4.0	Histic Leptosols	3.11	1.8	Dystric Cambisols	5.41	9.6	Mainly Calcaric Leptosols	3.4*	4.0
	Elmton	1.2		Cegin	1.2	Dystric Cambisols	5.41	10.2	Dystric Arenosols	5.5	2.6	Calcaric Cambisols	5.11	3.1
Eutric Cambisols	Hospford	0.1		Clifton	1.6		6.11	10.2	Eutric Luvisols	5.71	3.8	Dystric Cambisols	5.41	9.6
	Arrow	0.5		Dunkeswick	2.4	Stagnic Podzols	6.4 *	1.4	Dystric Cambisols	6.11	3.2	Dystric Arenosols	5.51/5.52	2.0
Calcaric Cambisols	Panholes	1.0		Wickham	2.3	Orthic Umbrisols	6.12	0.5	Haplic Podzols	6.31	0.9	Eutric Luvisols	5.71	3.8
Eutric Arenosols	Newport	1.8		Salop	1.1	Haplic Podzols	6.31	2.6	Luvic & Cambic Stagnosols	7.11	10.0	Chromic Luvisols or Alisols	5.81/2	2.0
Calcaric proto-vertic Cambisols	Hanslope	3.9	Stagnic Umbrisols	Wilcocks	2.9					7.13	4.2	Dystric Cambisols	6.11	3.2
	Evesham	1.8	Dystric Cambisols	Rivington	1.1							Luvic Stagnosols	7.11	10.0
Luvic Stagnosols	Dunkeswick	1.3		Denbigh	4.7									
	Beccles	2.5		Manod	3.9									
	Wickham	2.5												
Total PET (%)		**18.8**			**25.2**			**26.6**			**34.3**			**37.7**

† IUSS (2014).
‡ Percentage of ecosystem type.

Table 2. Evaluation of the calibrated CENTURY 5 model predictions of year-specific mean topsoil organic carbon against measured data for the selected indicator soil types under different ecosystems.

Ecosystem	Number of data points	R^2	Equation†	Root mean measured change in % OC (s.d.)	RMSE of predicted change in % O.C.	ME of predicted change	% of predictions with correct change trend
A.	**All indicator soil types**						
Arable	11	0.007	$\hat{y} = -0.0245x + 0.0061$	0.30 (±0.12)	0.32	-0.35	55
Managed Grassland	10	0.006	$\hat{y} = -0.0565x - 0.0971$	0.73 (±0.35)	0.79	-1.51	60
Semi-natural Grassland or heath	6	0.902	$\hat{y} = 0.616x + 0.0711$	5.16 (±3.37)	2.16	0.63	100
Deciduous Woodland	8	0.847	$\hat{y} = 0.2851x + 0.647$	6.12 (±5.44)	4.73	0.28	63
Coniferous Woodland	7	0.003	$\hat{y} = 0.0487x - 0.559$	0.78 (±0.42)	1.20	-1.39	43
All Ecosystems	42	0.455	$\hat{y} = 0.363x - 0.033$	3.34 (±2.99)	2.31	0.46	62
B.	**All indicator soil types excluding those with an unacceptable prediction‡**						
Arable	8	0.191	$\hat{y} = 0.152x + 0.0113$	0.24 (±0.15)	0.22	0.08	75
Managed Grassland	8	0.280	$\hat{y} = 0.246x - 0.0841$	0.67 (±0.34)	0.50	0.02	75
Semi-natural Grassland or heath	6	0.902	$\hat{y} = 0.616x + 0.0711$	5.16 (±3.37)	2.16	0.63	100
Deciduous Woodland	8	0.872	$\hat{y} = 0.2742x + 0.4858$	6.54 (±5.69)	5.02	0.27	71
Coniferous Woodland	5	0.368	$\hat{y} = 0.5331x - 0.2417$	0.77 (±0.50)	0.60	0.27	60
All Ecosystems	35	0.696	$\hat{y} = 0.3648x - 0.0436$	3.70 (±3.28)	2.48	0.47	76

† $\hat{y}$ = the predicted value; x = the observed (measured) value.

‡ Unacceptable predictions are when modelling efficiency (ME) is negative and change of trend does not match measured trends

Table 3. Linear regression relationships between the initial topsoil organic carbon content and the annual rate of change in topsoil organic carbon (% organic carbon per year) of indicator soil types under arable, managed grassland, semi-natural grass or heath land and woodland ecosystems.

Data source	**Constant**	**Multiplier (yr^{-1})**	**Annual rate of change for mean initial OC content (%SOC yr^{-1})**	**Regression coefficient**
CENTURY prediction for all indicator soil types	0.039	-0.010	-0.019	0.6952
CENTURY prediction for all indicator soil types except unacceptable predictions	0.040	-0.010	-0.022	0.7770
All indicator soil types measured	0.080	-0.023	-0.054	0.7649
Bellamy *et al*, 2005 (measured)	0.060	-0.019	-0.046	0.7825

Table 4. CENTURY-simulated mean changes in topsoil organic carbon content (%) under UKCIP02 climate change scenarios for all indicator soil types under arable, managed grass and semi-natural grass or heath land ecosystems.

		Arable		**Managed grassland**		**Semi-natural grassland**	
		Mean	**c.i.** †	**Mean**	**c.i.**	**Mean**	**c.i.**
Topsoil organic carbon % at the start of the simulation		2.18	0.21	3.92	0.45	9.78	4.16
Change in topsoil organic carbon % under different emission scenarios	High	-0.05	0.12	-0.39	0.36	-1.54	2.56
	Medium High	-0.03	0.11	-0.27	0.36	-1.49	1.95
	Medium Low	-0.03	0.11	-0.27	0.36	-1.49	2.39
	Low	-0.03	0.12	-0.29	0.36	-1.50	2.41

† c. i. = confidence interval.

Figure 1

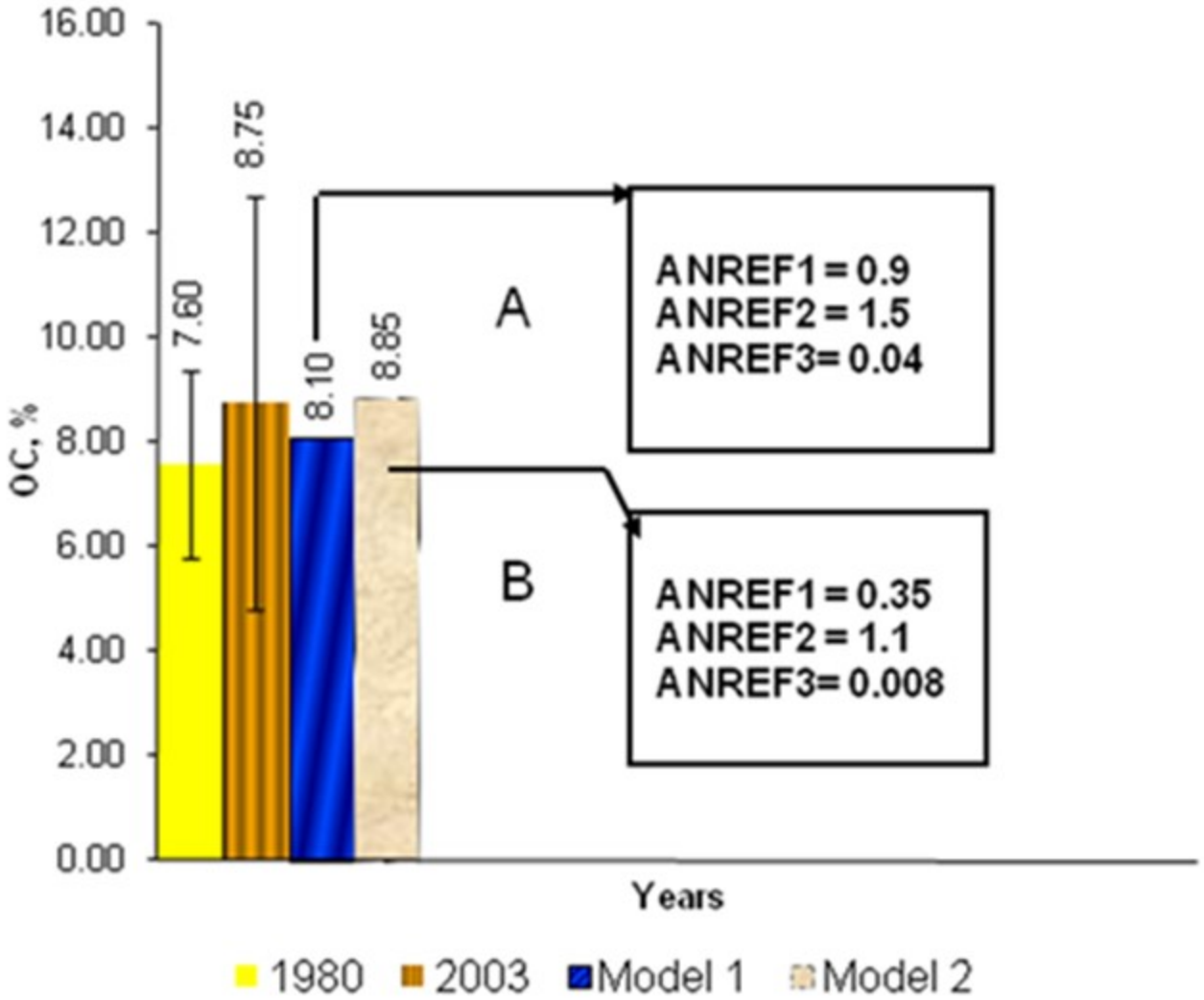

16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
OC, %
7.60
8.75
8.10
8.85
A
B
ANREF1 = 0.9
ANREF2 = 1.5
ANREF3= 0.04
ANREF1 = 0.35
ANREF2 = 1.1
ANREF3= 0.008
Years
1980
2003
Model 1
Model 2

Figure 2

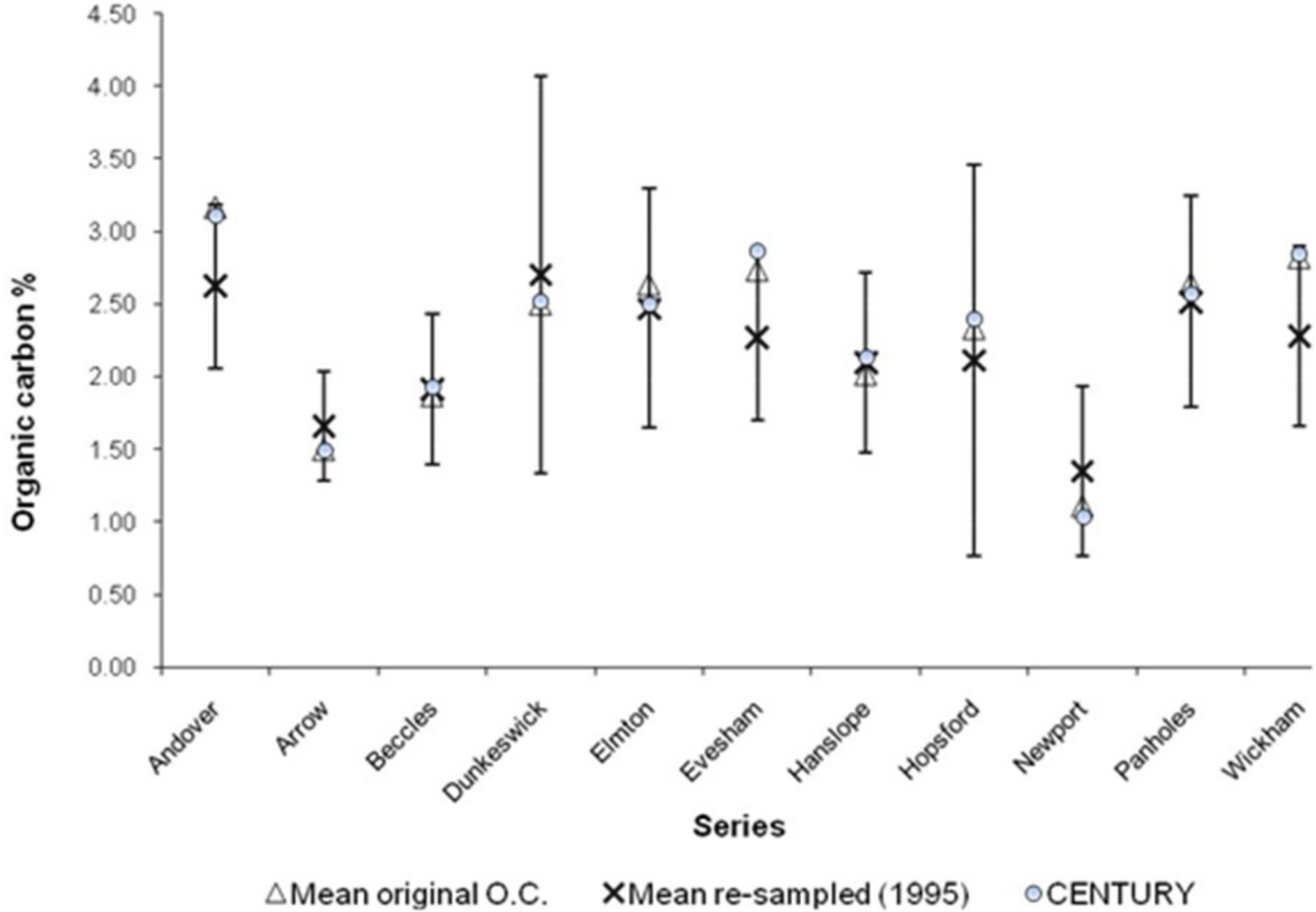

Organic carbon %
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Andover
Arrow
Beccles
Dunkeswick
Elmton
Evesham
Hanslope
Hopsford
Newport
Panholes
Wickham
Series
△Mean original O.C.
×Mean re-sampled (1995)
○CENTURY

Figure 3

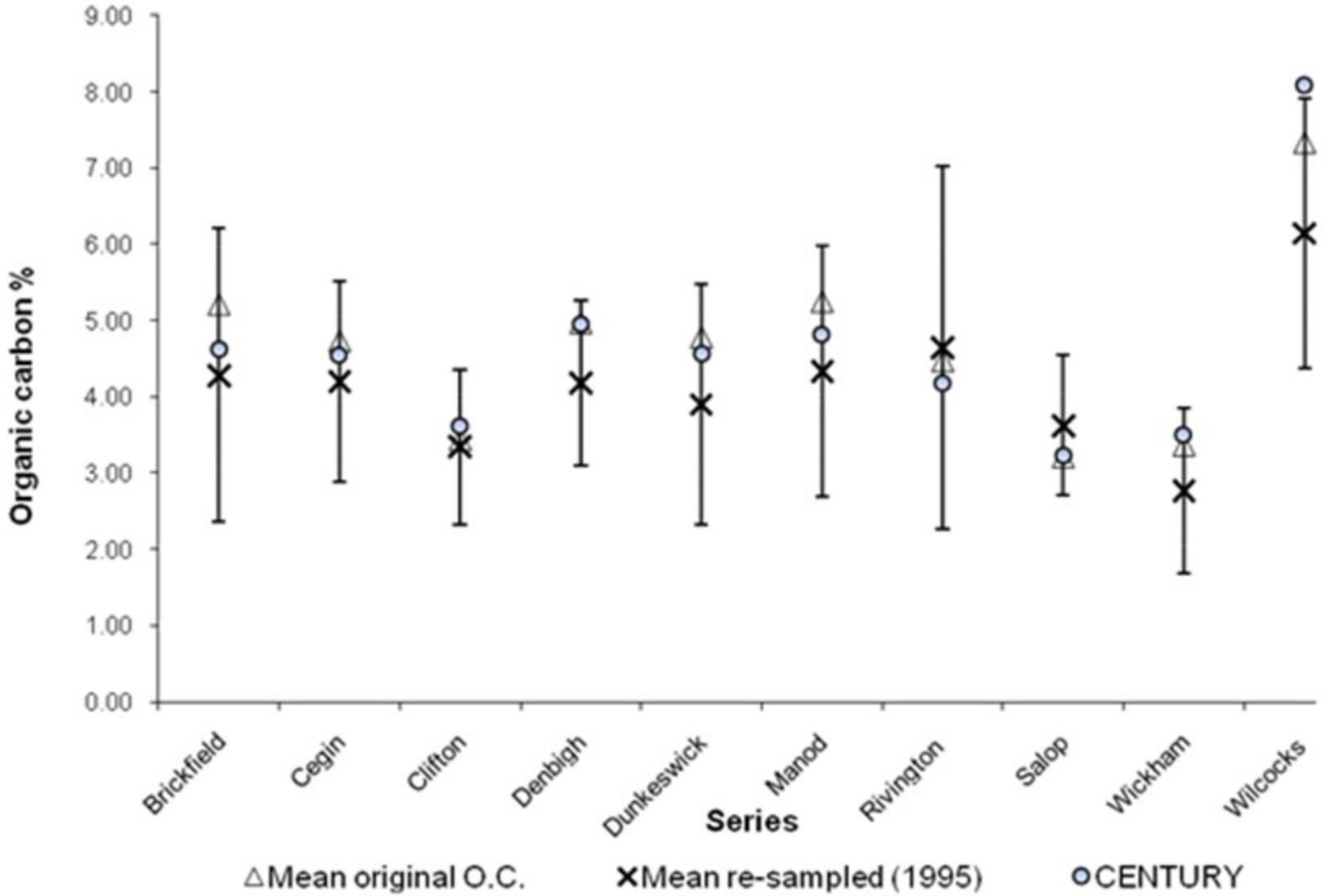
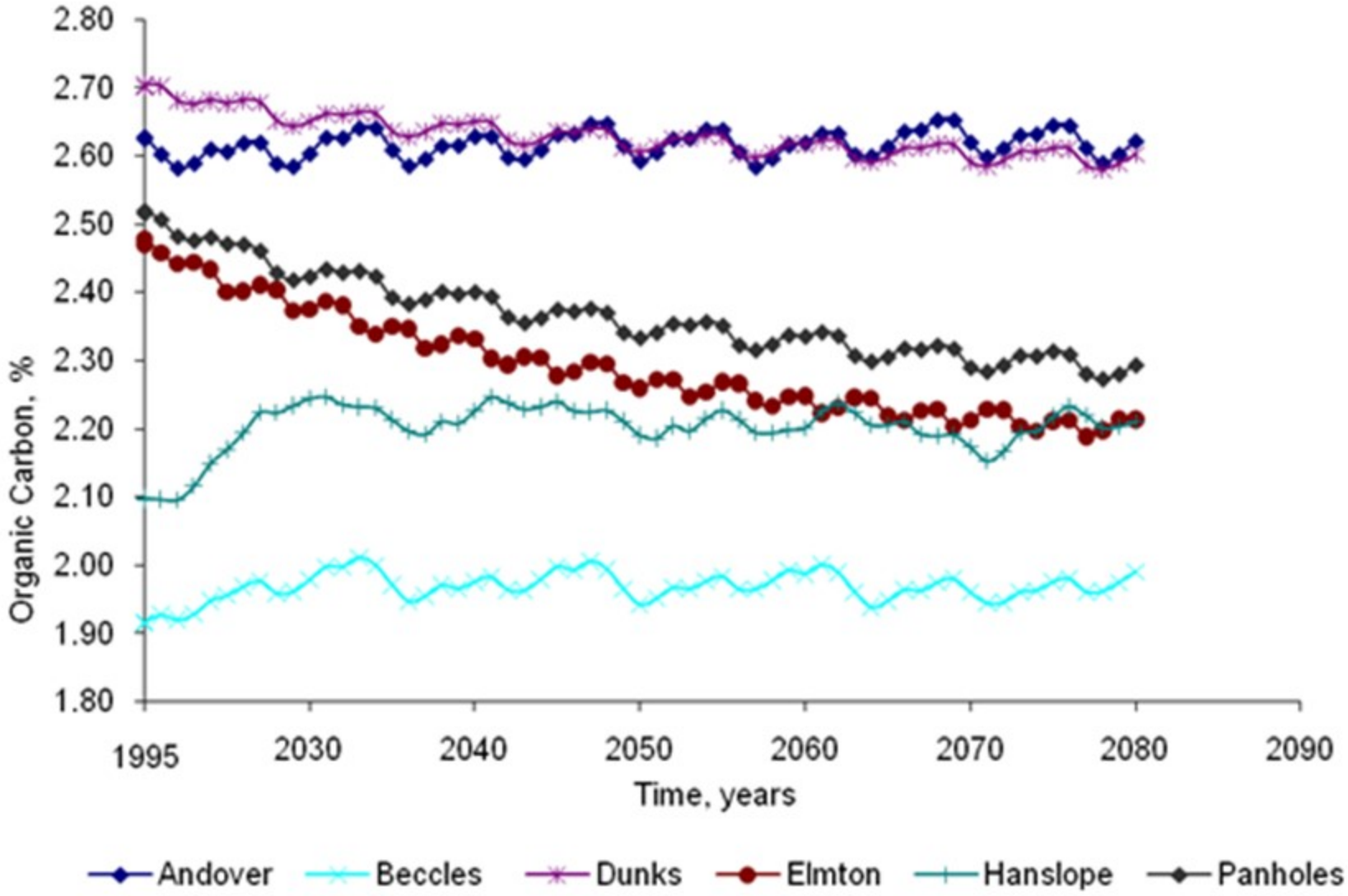

9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Organic carbon %
Brickfield
Cegin
Clifton
Denbigh
Dunkeswick
Manod
Rivington
Salop
Wickham
Wilcocks
Series
△Mean original O.C.
×Mean re-sampled (1995)
○CENTURY

Figure 4


2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80
Organic Carbon, %
1995
2030
2040
2050
2060
2070
2080
2090
Time, years
Andover
Beccles
Dunks
Elmton
Hanslope
Panholes



https://dspace.org/

Evaluating changes in soil organic matter with climate using CENTURY in England and Wales

Sakrabani, Ruben; Hollis, John

2018-03-29
American Society of Agronomy
http://dx.doi.org/10.2134/jeq2017.08.0310
Ruben Sakrabani and John Hollis. Evaluating changes in soil organic matter with climate using CENTURY in England and Wales. Journal of Environmental Quality, Vol. 47, Issue 4, 2018, pp. 695-703

Downloaded from a DSpace repository. https://dspace.org/