Biol Fertil Soils (1998) 27:236–241

ORIGINAL PAPER

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Regional estimates of carbon sequestration potential: linking the Rothamsted Carbon Model to GIS databases

Received: 1 December 1997

Abstract Soil organic matter (SOM) represents a major pool of carbon within the biosphere. It is estimated at about 1400 Pg globally, which is roughly twice that in atmospheric CO_2. The soil can act as both a source and a sink for carbon and nutrients. Changes in agricultural land use and climate can lead to changes in the amount of carbon held in soils, thus, affecting the fluxes of CO_2 to and from the atmosphere. Some agricultural management practices will lead to a net sequestration of carbon in the soil. Regional estimates of the carbon sequestration potential of these practices are crucial if policy makers are to plan future land uses to reduce national CO_2 emissions. In Europe, carbon sequestration potential has previously been estimated using data from the Global Change and Terrestrial Ecosystems Soil Organic Matter Network (GCTE SOMNET). Linear relationships between management practices and yearly changes in soil organic carbon were developed and used to estimate changes in the total carbon stock of European soils. To refine these semi-quantitative estimates, the local soil type, meteorological conditions and land use must also be taken into account. To this end, we have modified the Rothamsted Carbon Model, so that it can be used in a predictive manner, with SOMNET data. The data is then adjusted for local conditions using Geographical Information Systems databases. In this paper, we describe how these developments can be used to estimate carbon sequestration at the regional level using a dynamic simulation model linked to spatially explicit data. Some calculations of the potential effects of afforestation on soil carbon stocks in Central Hungary provide a simple example of the system in use.

Key words Soil organic carbon · Geographical Information Systems · Modelling · Carbon sequestration · Hungarian soils

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Introduction

In this paper we describe the Global Change and Terrestrial Ecosystems Soil Organic Matter Network (GCTE SOMNET; Smith et al. 1996a) and show how data from this network has been used to modfiy the Rothamsted Carbon Model (RothC-26.3; Coleman and Jenkinson 1996), thus allowing RothC to be used for regional carbon studies. A study of the potential effects of afforestation on soil organic carbon (SOC) stocks in Central Hungary is presented as an illustration of how the combined system works.

GCTE SOMNET

Soil organic matter (SOM) plays a central role in nutrient (N, P, S, K) availability, soil stability and the flux of greenhouse gases between the land surface and the atmosphere. It represents a major pool of carbon within the biosphere. It is estimated at about 1400 Tg globally, roughly twice that in atmospheric CO_2, and can act as both a source and a sink for carbon and plant nutrients.

To facilitate scientific progress in predicting the effects on SOM of changes in land use, agricultural practice and climate, a network of SOM modellers and long-term dataholders (SOMNET) was established in 1995. SOMNET has since attracted contributions from 29 leading SOM modellers and over 70 long-term experimentalists around the world (Smith et al. 1996a, b; Powlson et al. 1998).

SOMNET has been adopted by the International Geosphere-Biosphere Program (IGBP) GCTE programme as a core project for its focus on SOM. The SOMNET group has been invited to participate in the Intergovernmental Panel on Climate Change (IPCC) Joint Working Group (with Organisation for Economic Co-operation and Development (OECD)) on Methodologies for Establishing National CO_2 Inventories. Long-term datasets and models selected from SOMNET have been used to complete the most comprehensive evaluation of SOM models undertaken to date (Smith et al. 1997a). The process began at a NATO-funded Advanced Research Workshop held at IACR-Rothamsted (Powlson et al. 1996). In this exercise, nine leading SOM models were compared for performance in simulating 12 datasets that covered different land uses (arable, grassland, forest), climatic zones and management practices. Only four models were able to simulate all land uses (RothC, NCSOIL, CENTURY and SOMM), and a group of six models (RothC, CENTURY, DAISY, CANDY, NCSOIL and DNDC) performed significantly better than did three others (Smith et al. 1997a, b). Model performance was assessed statistically for model fit to measured data.

In addition to the model comparison exercise, datasets from SOMNET (Smith et al. 1996c) have also been used to estimate the potential for carbon sequestration in agricultural soils in the European Union (Smith et al. 1997c, 1998a) and the wider Europe (Smith et al. 1997d). In these studies, we have shown that agronomically realistic scenarios could sequester up to 10% of the anthropogenic CO_2 produced in Europe each year, or up to 2% of that produced globally. We have also used SOMNET data to estimate the potential consequences of land use change following the British BSE crisis (Smith et al. 1996d).

The SOMNET project has yielded over 60 peer-reviewed scientific papers (e.g.: Powlson et al. 1996; Molina and Smith 1998; Smith et al. 1998b; Smith et al. 1997b). The project has also yielded a book of model and experimental metadata (Smith et al. 1996b) and a metadata database containing detailed information on all the major long-term experiments and SOM models (Smith et al. 1996a) mounted for free global access (on the World Wide Web at URL http://saffron.res.bbsrc.ac.uk/cgi-bin/somnet).

Regional scale SOM modelling

Concern about the effect of changes in climate, land use and management has led to an increased interest in studies of carbon cycling at regional and global scales (Post et al. 1982; Prentice and Fung 1990; Jenkinson et al. 1991; Donigan et al. 1994; Parshotam et al. 1995; Smith et al. 1997c, d, 1998a; King et al. 1997). Previous studies of regional and global scale terrestrial carbon cycling have used regressions based on long-term experiments (Smith et al. 1997c, d, 1998a) aggregated climatic data and assumed soil properties for major biomes combined with modelling (Jenkinson et al. 1991). Regressions based on Global Circulation Models (GCMs), vegetation distribution (Prentice and Fung 1990) and global soil carbon and vegetation distributions (Post et al. 1982; King et al. 1997) have also been used. The stock of SOM in soil is largely determined by the input of carbon from plant residues and the rate at which this input decays and releases CO_2 to the atmosphere; the SOM balance is altered when changes in climate and land use affect the amount and decomposability of plant input to the soil (Parshotam et al. 1995).

By linking Geographic Information Systems (GIS) that contain detailed information on soils, land use and climate to dynamic simulation models for the turnover of organic carbon, it is possible to estimate the impacts of land use and climatic changes on carbon stocks in soil. Recent studies have applied RothC to natural forests and grasslands in New Zealand (Parshotam et al. 1995) and global studies (King et al. 1997), CENTURY (Parton et al. 1988) to agroecosystems in the central United States (Donigan et al. 1994) and EPIC (Williams and Renard 1985; Sharpley and Williams 1990a, b) for tillage impacts on the US Corn Belt (Lee et al. 1993). This approach allows more flexible manipulation of data and graphical display of outputs in a spatial form. Site specific input data for the model can also be provided at high resolution.

GIS-linked modelling is a useful tool for large scale carbon cycle studies, allowing current estimates of regional carbon sequestration to be refined. It is also possible to analyse the sensitivity of particular combinations of predominant land use, soil and weather characteristics to perturbations in climate, land use and management. Hence, particularly sensitive systems and systems with great potential for carbon sequestration can be identified.

The Inert Organic Matter (IOM) and plant input parameters needed to run RothC in a predictive mode were estimated independently. IOM was estimated from a regression of SOC against fitted IOM at a range of sites with radiocarbon data (Falloon et al. 1998). Plant inputs were estimated as the mean of plant inputs at equilibrium for three land use types (arable, grassland and forest) at 60 modelled SOMNET sites. RothC was linked to a GIS database for an area of central Hungary. This enabled us to make preliminary estimates of the impacts of land use change on SOM reserves and regional carbon balances in this part of Hungary.

Materials and methods

Study area and GIS

The chosen study area (24,804 km^2) is specified in Table 1. The GIS platform used was ArcView.

Table 1 Study area

	Lower left of window		Upper right of window	
	X	Y	X	Y
UTM[a] (34)	5183816.64	325048.59	5340133.61	472979.10
Spherical system	46.784	18.708	48.213	20.636
Hungarian EOV[b]	160000	624000	320000	768000

[a] Universal Terrain Model
[b] Uniform National Projection of Hungary

Soils

Soil data were taken from the 1:500,000 Hungarian HunSOTER database (Pásztor et al. 1996, Szabó et al. 1996). The window contained 275 representative soil profiles from a dataset of 1,361 for the whole of Hungary. HunSOTER is a country scale GIS data source with an integrated hierarchy of point and polygon layers. The profiles were originally sampled in 1992. Only the uppermost horizon data were used in this study. Data were converted to a standard depth of 30 cm without accounting for variability in horizon thickness. The soil variables used from this dataset were: organic carbon content (SOC) %, clay content (%) and Bulk density (Mg m^{-3}). The profile data were linked to 351 SOTER unit polygons (representing areas with unique soil, land form and lithology characteristics) for the window. Where profile data were missing (3 polygons; soil units 6, 394 and 933), a mean over the dataset for the whole region was used. The dataset was used to calculate the soil IOM content in the absence of radiocarbon data (Falloon et al. 1998) and SOC to 30 cm depth.

Land use

Land use data were taken from the CORINE database for Hungary (scale 1:100,000 – Büttner et al. 1995a, b; Büttner 1997), for the representative window, and contained 6,470 polygons. The land use polygon data were exploded in ArcView using a custom script. This produced a total of 7,529 polygons due to multi-part polygons in the original dataset. The 44 original land use codes were rationalised into four codes: (1) arable (6 original codes), (2) grassland (8 original codes), (3) forest (6 original codes) and (4) other uses (including marsh, water bodies, urban areas and so on; 24 original codes),

Meteorology

Long-term mean monthly temperature, rainfall and evaporation data from 1931–1960 were used (Varga-Haszonits 1977). This provided 17 precipitation stations, 14 temperature stations and six evaporation stations over the area. A point layer containing the long-term averaged meteorological data and the site locations was created.

Layer linkage

A custom script was written to find the centres of all land use polygons. The land use polygon centres were then linked to each of the evaporation, temperature and rainfall station layers, using the nearest station for each meteorological attribute for each polygon. This provided a linked land use/meteorological layer. Meteorological values were not interpolated between stations in this case study. A more refined calculation might require interpolation to account for the effects of topography and elevation. The soil layer, based on SOTER units, was overlaid upon the linked land-use/meteorological layer, using a custom script, and produced 12,086 polygons that represented a unique combination of land use, soil and meteorology. Polygons with land-use code 4 were excluded leaving the 9,888 polygons actually used in the modelling exercise.

Model linkage

The original source code of the model was altered to take input from a fixed width ASCII file produced by the GIS and to write results to a new ASCII file. The results file was loaded into Excel, Access and GENSTAT for analysis and into ArcView for visualisation.

Scenarios

The model was run to equilibrium under two different scenarios: (1) using the default plant input values derived from a dataset of equilibrium land use treatments at 60 sites across the globe (with default plant inputs set at 3.55 tC ha^{-1} $year^{-1}$ for arable, 3.72 tC ha^{-1} $year^{-1}$ for grasslands and 7.09 t Cha^{-1} $year^{-1}$ for forests) and (2) giving the analytical solution of plant inputs required to fit modelled SOC to measured SOC. This allowed a comparison of the two proposed methods for estimating plant inputs across all polygons. Practically, soil properties were taken into account, but little consideration for carbon inputs were made.

As a simple demonstration scenario, we examined the effect on SOC after 50 and 100 years following afforestation of all current arable land (assuming instantaneous forest establishment). It should be stressed that this scenario was chosen to demonstrate the methodology and does not reflect a realistic land use change option. Sequential changes in land use may be included in future calculations.

Results and discussion

The total SOC stock for the whole area was calculated as 1.40 Tg, which increased to 1.80 Tg 50 years after afforestation, and 1.89 Tg after 100 years. The change in SOC can be seen in Figs. 1 and 2. Figure 2 shows a higher proportion of darker shaded areas, representing higher SOC after afforestation. This represents a change of 28% over 50 years or 35% over 100 years (0.56% $year^{-1}$ for 0–50 years, 0.35% $year^{-1}$ over 100 years). Hence, afforesting all arable land gives a carbon sequestration potential for this area of 0.49 Tg C over 100 years.

The results suggest that the annual increase in SOC was considerably lower between 50 and 100 years following afforestation than for 0–50 years. For the same scenario, using Smith et al.'s (1997c) regression equation for the yearly percentage change in SOC, the total SOC stock 100 years after afforestation of all arable land would be 1.97 Tg, which is slightly higher than our

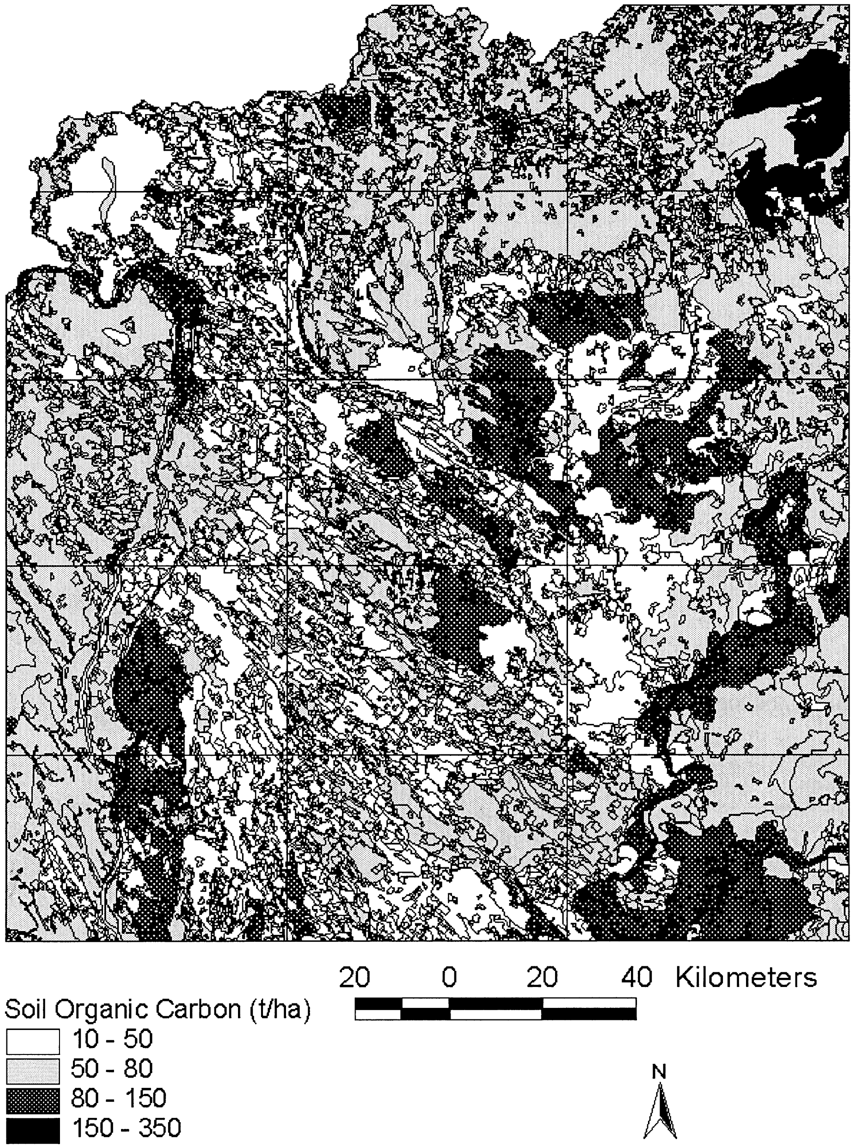

Fig. 1 Soil organic carbon before land use change scenario (1997)

estimate of 1.89 Tg. We have more confidence in our estimate, since we have explicitly accounted for differences in soil type and climate.

The mean plant inputs (t C ha^{-1} $year^{-1}$) fitted to match measured SOC values (assumed to be at equilibrium) were as follows: arable = 5.83 (SD = 2.74), grassland = 4.33 (SD = 2.44) and forest = 3.81 (SD = 2.41). The fitted plant inputs account only for soil type differences and not for variations in SOC due to land use, because only one profile per soil unit was available. A *t*-test between the default plant inputs and the plant inputs fitted to give SOC values at equilibrium shows no significant difference, but there is much variability among the fitted inputs. The inputs under forest and grassland are lower than under arable, which is in contrast to our default values, and most unreasonable. This may be explained two ways. First, large areas of forests are on soils with relatively low SOC values from HunSOTER, reducing the mean equilibrium input under forest. Second, assuming most soils were sampled under arable land use, arable SOC tends to be lower than forest SOC at equilibrium, and as the decomposable plant material/resistant plant material ratio of forest is lower than that of arable, lower plant inputs are needed to attain the same SOC values under forest. Some areas underlain by soils with high SOC values actually experienced a decline in SOC following afforestation for 100 years. For example, a soil with a SOC value of 90 t C ha^{-1} could require up to 13 t C ha^{-1} $year^{-1}$ plant inputs, and assuming our default forest input of only 7.09 t C ha^{-1} $year^{-1}$, SOC will decline following afforestation.

There may be errors introduced by estimating the IOM content of the soil, especially in highly organic and waterlogged soils (especially histosols and fluvisols; Falloon et al. 1998) and in calculating SOC to a 30 cm depth, as the sample depth was variable. The input of plant carbon to soil under forest, grassland and arable

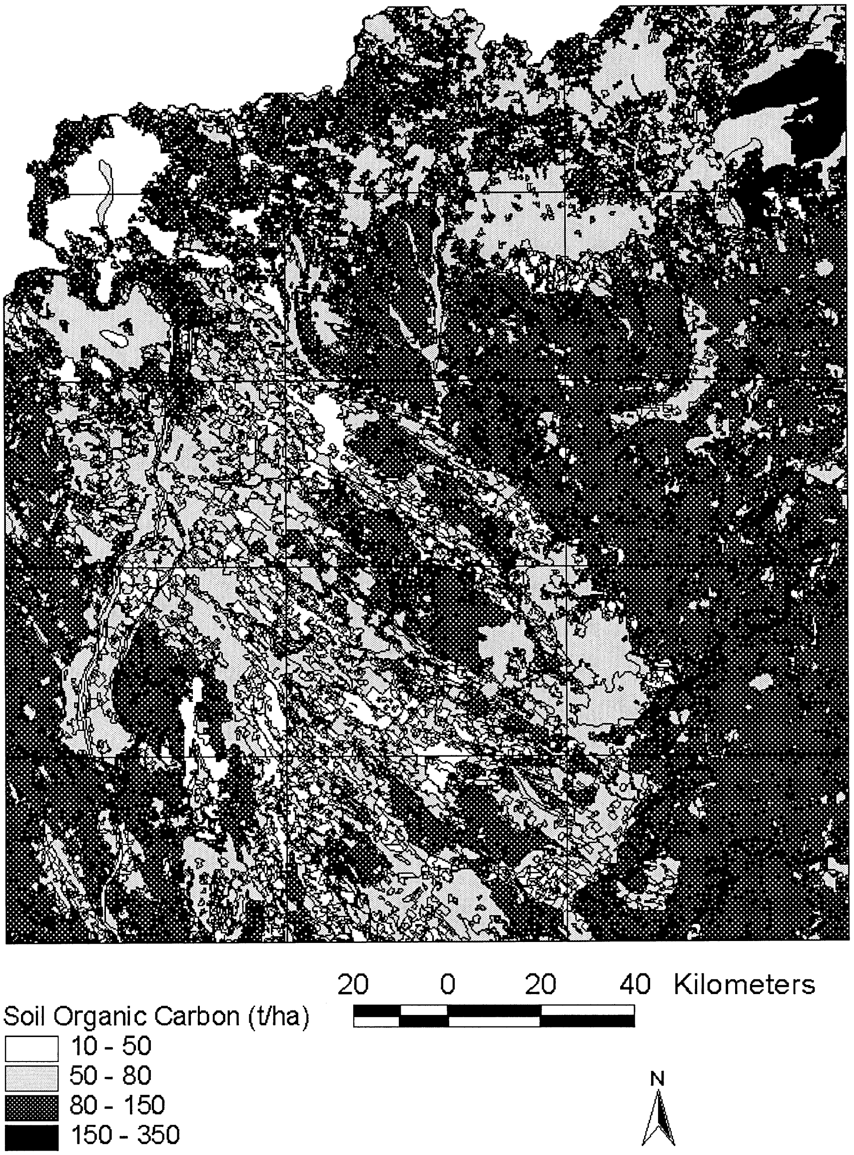

Fig. 2 Soil organic carbon after land use change scenario (2097)

land use could be estimated with more confidence if each soil type were sampled for these three land uses or linked with a dynamic net primary production model.

This study does not include the additional carbon sequestered in the standing woody biomass, which would further increase the carbon stored in the terrestrial system. In regenerating temperate woodland, Jenkinson (1971) found the standing woody biomass to have accumulated approximately 1.52 times as much carbon as was found in the soil after 86 years. Using this ratio, the above ground biomass would sequester 0.75 Tg, giving a total of 1.23 Tg C sequestered on the arable land area. If a proportion of land were to be afforested, the biomass accumulated in the trees could be used as a substitute for fossil fuels (Sampson et al. 1993), thus further mitigating fossil fuel derived CO_2–carbon.

These preliminary calculations show how coupling a detailed GIS database with a dynamic simulation model can refine estimates of regional SOC stocks and sequestration potential. The system should provide a flexible and powerful way to assess how different scenarios for land use, management and climatic change can affect carbon dynamics at the regional scale. Forecast climate data from GCMs could prove useful in predicting the effects of climate change.

Acknowledgements We would like to thank László Pásztor, György Várallyay, Péter Csathó and Tamás Németh (RISSAC) for kindly supplying input data and site information, and David Jenkinson and Nabeel Mirza (IACR-Rothamsted) for assistance with modelling and GIS. This work was supported by a grant from the UK Biotechnology and Biological Sciences Research Council. IACR receives grant-aided support from the UK Biotechnology and Biological Sciences Research Council.

References

Büttner G (1997) Land Cover – Hungary; final technical report to phare. FOMI, Budapest

Büttner G, Csató E, Maucha G (1995a) The CORINE land cover – Hungary Project. In: 17th International Cartographic Association Conference, Barcelona, Spain. Abstract Book. ICA, Barcelona, Spain, p 1813

Büttner G, Csató E, Maucha G (1995b) The CORINE land cover – Hungary Project. In (Harnos, Z) Proceedings of the International Conference of Environmental Informatics, Budapest. Computer and Automation Research Institute, Hungarian Academy of Sciences, Budapest, pp 54–61

Coleman K, Jenkinson DS (1996) RothC-26.3. A model for the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU (eds) Evaluation of soil organic matter models using existing, long-term datasets. NATO ASI Series I, vol 38. Springer, Berlin Heidelberg New York, pp 237–246

Donigan AS, Barnwell TO, Jackson RB, Patwardhan AS, Weinrich KB, Rowell AL, Chinnaswammy RV, Cole CV (1994) Assessment of alternative management practices and policies affecting soil carbon in agroecosystems of the central United States. EPA/600/R-94/067. Environmental Research Laboratory, Athens, Ga

Falloon P, Smith P, Coleman K, Marshall S (1998) Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the Rothamsted Carbon Model. Soil Biol Biochem (in press)

Jenkinson DS (1971) The accumulation of organic matter in soil left uncultivated. Rothamsted Report for 1970, part 2:113–137

Jenkinson DS, Adams DE, Wild A (1991) Model estimates of CO_2 emissions from soil in response to global warming. Nature 351:304–306

King AW, Post WM, Wullschleger SD (1997) The potential response of terrestrial carbon storage to changes in climate and atmospheric CO_2. Clim Change 35:199–227

Lee JJ, Phillips DL, Liu R (1993) The effect of trends in tillage practices on erosion and carbon content of soils in the US Corn Belt. Water Air Soil Pollut 70:389–401

Molina JAE, Smith P (1998) Modelling carbon and nitrogen processes in soil. Adv Agron 62:253–298

Parshotam A, Tate KR, Giltrap DJ (1995) Potential effects of climate and land- use change on soil carbon and CO_2 emissions from New Zealand's indigenous forests and unimproved grasslands. Weather Clim 15/2:3–12

Parton WJ, Stewart JWB, Cole CV (1988) Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5:109–131

Pásztor L, Szabó J, Várallyay G (1996) Digging deep for global soil and terrain data. GIS Eur 5/8:32–34

Post WM, Emmanuel WR, Zinke PJ, Stangenberger AG (1982) Soil carbon pools and world life zones. Nature 298:156–159

Powlson DS, Smith P, Smith JU (1996) Evaluation of soil organic matter models using existing, long-term datasets. NATO ASI SeriesI, vol 38. Springer, Berlin Heidelberg New York, pp 81–98

Powlson DS, Smith P, Coleman K, Smith JU, Glendining MJ, Körschens M, Franko U (in press) A European network of long-term sites for studies on soil organic matter. Soil Till Res

Prentice KC, Fung IY (1990) The sensitivity of terrestrial carbon storage to climate change. Nature 346:48–51

Sampson RN, Wright LN, Winjum JK, Kinsman JD, Benneman J, Kürsten E, Scurlock JMO (1993) Biomass management and energy. Water Air Soil Pollut 70:139–159

Sharpley AN, Williams JR (eds) (1990a) EPIC – erosion/productvity impact calculator. 1. Model documentation. USDA Technical Bulletin No. 1768, Washington, DC

Sharpley AN, Williams JR (eds) (1990b) EPIC – rrosion/productvity impact calculator. 2. User manual. USDA Technical Bulletin No. 1768, Washington, DC

Smith P, Powlson DS, Smith JU, Glendining MJ (1996a) The GCTE SOMNET. A global network and database of soil organic matter models and long-term datasets. Soil Use Manage 12:104

Smith P, Smith JU, Powlson DS (1996b) Soil Organic Matter Network (SOMNET): 1996 model and experimental metadata. GCTE Report 7. GCTE Focus 3 Office, Wallingford, Oxon

Smith P, Powlson DS, Glendining MJ (1996c) Establishing a European soil organic matter network (SOMNET). In: Powlson DS, Smith P, Smith JU (eds) Evaluation of soil organic matter models using existing, long-term datasets. NATO ASI Series I, vol 38. Springer, Berlin Heidelberg New York, pp 81–98

Smith P, Smith JU, Powlson DS (1996d) Moving the British cattle herd. Nature 381:15

Smith P, Smith JU, Powlson DS, McGill WB, Arah JRM, Chertov OG, Coleman KC, Franko U, Frolking S, Jenkinson DS, Jensen LS, Kelly RH, Klein-Gunnewiek H, Komarov AS, Li C, Molina JA, Mueller T, Parton WJ, Thornley JM, Whitmore AP (1997a) A comparison of the performance of nine soil organic matter models using seven long-term experimental datasets. In: Smith P, Powlson DS, Smith JU, Elliott ET (eds) Evaluation and comparison of soil organic matter models using datasets from seven long-term experiments. Geoderma 81:153–225

Smith P, Powlson DS, Smith JU, Elliott ET (1997b) Evaluation and comparison of soil organic matter models using datasets from seven long-term experiments. Geoderma 81:1–225

Smith P, Powlson DS, Glendining MJ, Smith JU (1997c) Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change Biol 3:67–80

Smith P, Powlson DS, Glendining MJ, Smith JU (1997d) Opportunities and limitations for C sequestration in European agricultural soils through changes in management. In: Lal R, Kimble JM, Follett RF, Stewart BA (eds) Management of carbon sequestration in soil. Adv Soil Sci, pp 143–152

Smith P, Powlson DS, Margaret MJ, Smith JU (1998a) Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. Global Change Biol (in press)

Smith P, Andrén O, Brussaard L, Dangerfield M, Ekschmitt K, Lavelle P, Tate K (1998b) Soil biota and global change at the ecosystem level: describing soil biota in mathematical models. Global Change Biol (in press)

Szabó J, Várallyay G, Pásztor L (1996) HunSOTER, a digitised database for monitoring changes in soil properties in Hungary. In: (Milan Sanka I, ed) Proc. Soil Monitoring in the Czech Republic, Brno, 31st May–1st June 1995. Central Institute for Supervising and Testing in Agriculture, Brno, pp 150–156

Varga-Haszonits Z (1977) Agrometeorologia. Mezogazdasagi Kiado, Budapest

Williams JR, Renard KG (1985) Assessment of soil erosion and crop productivity with process models (EPIC). In: Follett RF, Stewart BA (eds) Soil erosion and crop productivity. ASA/CSSA/SSSA, Madison, Wis., pp 67–103