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A European network of long-term sites for studies on soil organic matter

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Abstract

In this paper we describe the GCTE global Soil Organic Matter Network (SOMNET) before focusing on the European network of long-term sites. We then select two examples from the European site network and demonstrate how such data can be used to (a) track long-term changes in soil organic matter, (b) evaluate and compare soil organic matter models, and (c) make rough estimates of the potential for carbon (C) sequestration in soils at the regional (European) level. Our simple calculations based on only two long-term experiments suggest that amendment of arable soils with 10 Mg ha^{-1} of organic manure could lead to an increase in current total European soil C stock to 30 cm of about 4.8% over 90 yr, a scenario with limited potential for sequestering C. Similarly, afforestation through natural woodland regeneration of 30% of current arable land (surplus to requirements by 2010) could lead to an increase in current total European soil C stock of 12.4% over 100 yr. This is equivalent to 43 Tg C yr^{-1} or 3.8% of anthropogenic CO_2–C emissions from Europe. If temporary C storage in standing woody biomass is included in the estimate, the amount of C sequestered is quadrupled and could account for 15.28% of Europe's annual CO_2–C emissions. This is equivalent to 2.8% of annual global anthropogenic CO_2–C emissions. These calculations are presented to demonstrate a simple technique for estimating rough C sequestration potentials but they do suggest some potential to sequester C in European agricultural soils. As a result, a more sophisticated approach using statistical relationships derived from a large number of long-term experiments was developed. The need for balancing the effects of these scenarios on soil C against other environmental considerations is discussed. Methods for improving estimates of the potential for soil C sequestration using the European site network are also discussed. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Soil organic matter (SOM) plays a central role in nutrient (N, P, S) availability, soil stability and the flux of trace greenhouse gases between land surface and the atmosphere. It represents a major pool of carbon (C) within the biosphere, estimated at about 1400×10^{15} g globally, roughly twice that in atmospheric CO_2 (Post et al., 1982), and can act as both a source and a sink for C and nutrients.

To facilitate scientific progress in predicting the effects on SOM of changes in land-use, practice and climate, the need for a network of SOM modellers and

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long-term dataholders has been recognised (Buurman, 1993; GCTE, 1992; Gregory and Ingram, 1996). During 1995 such a global network was established and was adopted by the International Geosphere-Bioshere Programme's (IGBP) Global Change and Terrestrial Ecosystems (GCTE) project as a core research project of its focus on soil organic matter (the GCTE SOMNET).

In this paper we provide a brief description of the GCTE SOMNET, and describe how we are using the European regional portion of this network to (a) study long-term changes in SOM dynamics, (b) to evaluate and compare SOM models, and (c) to begin to estimate the potential for C sequestration in European agricultural soils.

2. The GCTE somnet

During 1995, with the help of colleagues in the USA and Australia, we collected in-depth metadata (detailed information) on SOM models and long-term experiments from around the world by means of detailed questionnaires. The metadata was collated and entered on an ORACLE database on the Yacorba system at IACR-Rothamsted. Data input, output and display routines were written in ORACTCL and a World-Wide-Web page was established for free Internet access to the database via the Electronic Rothamsted Archive (ERA). The database came online in December 1995 (Smith et al., 1996d) at URL http://yacorba.res.bbsrc.ac.uk/cgi-bin/somnet. A book of summary metadata has been published (Smith et al., 1996b).

The GCTE SOMNET had attracted contributions from 27 leading SOM modellers and over 70 long-term experimentalists from all around the world (Smith et al., 1996b, d). The range of modelling approaches reflected among the SOMNET models have been reviewed by Molina and Smith (1997) and Smith et al. (1998c). Fig. 1 shows the global distribution of long-term experiments and models participating in the SOMNET programme.

SOMNET has rapidly become internationally recognised as an important scientific initiative in the following ways: (a) SOMNET has been adopted by the IGBP's GCTE programme as a core project of Focus 3.3.1 on Soil Organic Matter, (b) SOMNET has been invited to participate in the Intergovernmental Panel on Climate Change (IPCC) Working Group on Methodologies for Establishing National CO_2 Inventories, (c) long-term datasets and models selected from SOMNET have been used to complete the most comprehensive evaluation of soil organic matter models undertaken to date (Smith et al., 1998b, d), in a process begun at a NATO-funded Advanced Research Workshop held at IACR-Rothamsted (Powlson et al., 1996).

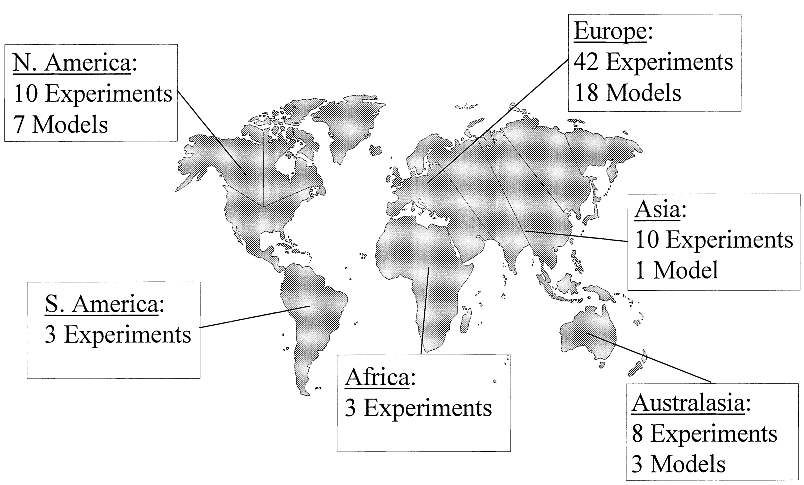

Fig. 1. The global distribution of 29 SOM models and 76 long-term SOM experiments participating in the GCTE Soil Organic Matter Network (SOMNET).

As well as the World-Wide-Web database and metadata directory (Smith et al., 1996b, d), the SOMNET project has yielded over 60 peer-reviewed scientific papers. These have appeared in a book of proceedings (of the NATO ARW; Powlson et al., 1996), a Geoderma Journal Special Issue (of the SOM model evaluation and comparison; Smith et al., 1998d) and a number of other journals.

The economic value of all data represented within SOMNET is estimated at over US$ 35 million (Smith et al., 1996d) based on estimated annual running costs of long-term experiments (Smith et al., 1996a). The contribution to this total from the 42 European datasets is over US$ 24 million.

Future developments in the GCTE SOMNET are likely to occur at the regional level, i.e. within North America (Paustian et al., 1996), Australia (Grace, 1996) and on other continents, and it is the European network of long-term sites that we will concentrate upon for the remainder of this paper. The distribution of long-term experiments within Europe is depicted in Fig. 2.

3. Long-term experiments

Ideally a long-term experiment should have accurate records, archived samples and continuity of treatments, as long as the treatments remain relevant and do not cause soil damage or crop failure. Some benefits and limitations of long-term experiments have recently been reviewed by Glendining and Poulton (1996).

In this paper we present two examples selected from within the European site network and show how these can be used to quantify changes in SOM over time, to evaluate and compare SOM models, and to begin to examine the potential for C sequestration in agricultural soils.

The examples we have chosen are the Bad Lauchstädt Static Fertilizer Experiment in Germany (Körschens and Müller, 1996) and the Broadbalk Wheat Experiment from Rothamsted, UK (Dyke et al., 1983; Hart et al., 1993).

The Bad Lauchstädt Static Fertilizer Experiment follows the effects of organic and mineral fertilizers on crops and soil over 90 yr. The site is in the cool temperate region (mean daily air temperature: 8.7°C; mean annual rainfall: 484 mm) on a Haplic Phaeozem (FAO) soil. Each field has a rotation of sugar beet (*Beta vulgaris* L.), spring barley (*Hordeum vulgare* L.), potatoes (*Solanum tuberosum* L.) and winter wheat (*Triticum aestivum* L.). The experiment is ploughed (mouldboard) to 20–30 cm in September to November every year. There are various treatments including a high fertilization treatment (30 Mg ha^{-1}

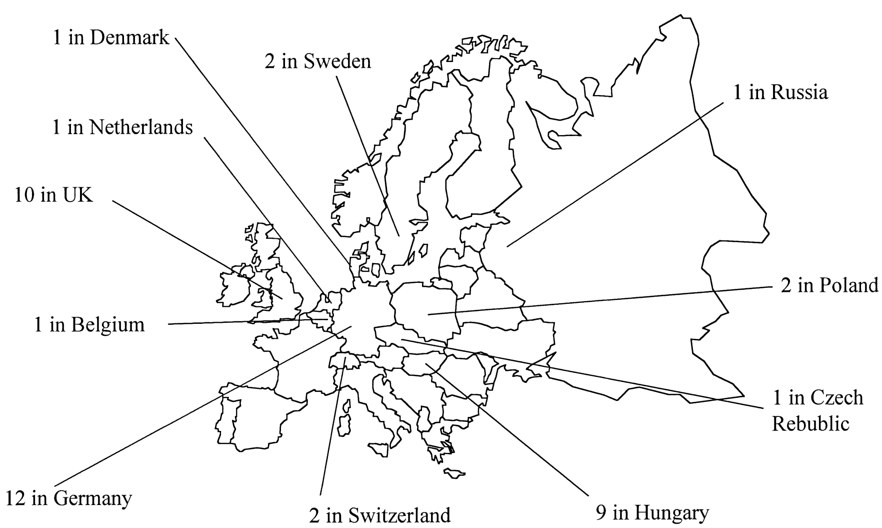

Fig. 2. The distribution of long-term soil organic matter experiments participating in the GCTE Soil Organic Matter Network (SOMNET) within Europe.

of farmyard manure every 2 yr plus various rates of inorganic NPK fertilizer), an organic manure treatment (20 Mg ha^{-1} of farmyard manure every second year), and a no fertilization treatment (zero inputs of fertilizer). Fig. 3 shows the changes in soil C content that have occurred during the past 40 yr of the experiment.

The total soil C content of the soil is determined every year on the main plots. As seen in Fig. 3, the wide range of fertilizer treatments since 1902 has led to a great difference in the total C content of the plots, especially between the highest fertilization level and the nil treatment. The results between 1972 and 1992 have been used by Körschens and Müller (1996) to demonstrate the following: (a) the different fertilization treatments caused a differentiation in percentage C content of 0.66%, (b) 20 Mg ha^{-1} farmyard manure plus NPK has had virtually the same effect on total C as has 30 Mg ha^{-1} farmyard manure, (c) NPK-fertilization has increased soil C content at all organic manuring levels, (d) at all farmyard manure levels without mineral N (i.e., PK only and nil treatments) lower total C contents were found compared to treatments with mineral N, (e) 20 Mg ha^{-1} farmyard manure increased the percentage total C content by 0.39%, compared to treatments without farmyard manure when averaged over all mineral fertilizer rates, and (f) 30 Mg ha^{-1} farmyard manure increased total C by 0.13% compared to 20 Mg ha^{-1}.

The Broadbalk Wheat Experiment was established in 1843 and since this time various rotations, including continuous winter wheat, have received various treatments of organic manure, inorganic fertilizers and no fertilization. The site is in the cool temperate region (mean daily air temperature: 9.1°C; mean annual rainfall: 728 mm) on a Chromic Luvisol (FAO) soil. The experiment is ploughed (tractor-mounted reversible plough) to 30 cm in autumn (fall) every year. In 1882, an area now known as Broadbalk Wilderness, was fenced and allowed to revert to natural woodland. The experiment has been used for many purposes (e.g., Powlson, 1994; Jones et al., 1994). Changes in soil organic C can be tracked over the course of the experiment and are depicted in Fig. 4 below (replotted from Jenkinson, 1990 and Jenkinson et al., 1987).

As seen in Fig. 4, application of farmyard manure has more than doubled soil organic C content (compared to no fertilization) over the course of the experi-

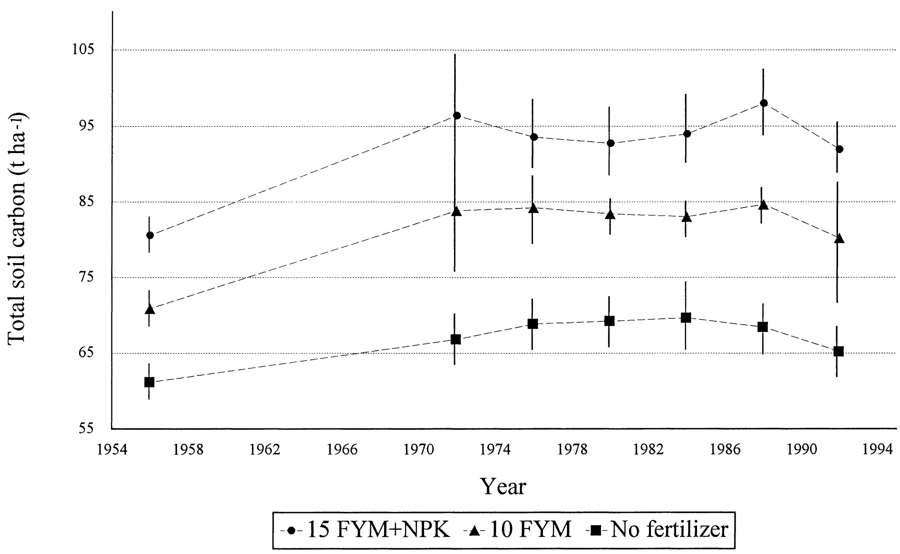

Fig. 3. Changes in total C content in the top 30 cm of soil in the Bad Lauchstädt Static Fertilizer Experiment during the past 40 yr. 15 FYM + NPK refers to the high fertilization treatment whereby 30 Mg ha^{-1} of farmyard manure and NPK inorganic fertilizer were added to soil every 2 yr (i.e., 15 Mg ha^{-1} yr^{-1}). 10 FYM refers to the treatment whereby 20 t ha^{-1} of farmyard manure was added to soil every 2 yr (i.e., 10 Mg ha^{-1} yr^{-1}). The no fertilizer plot has never received either organic or inorganic fertilizer. Dotted lines are shown only to improve clarity. Standard error bars are shown.

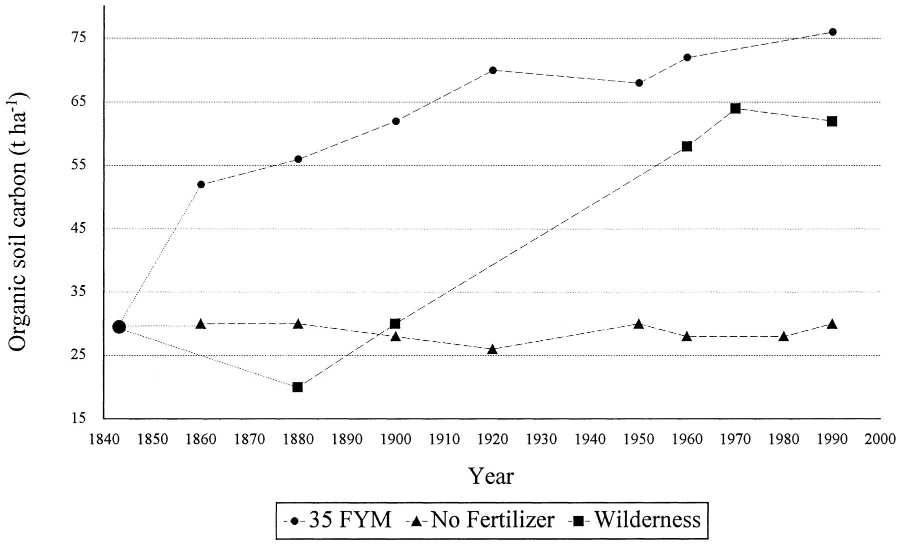

Fig. 4. Changes in total C content in the top 23 cm of soil in the Broadbalk Wheat Experiment and the Broadbalk Wilderness over 150 yr. 35 FYM refers to the treatment whereby 35 Mg ha^{-1} of farmyard manure was added to soil every year. The no fertilizer treatment has never received either organic or inorganic fertilizer. The Wilderness was fenced off in 1882 and allowed to regenerate to natural woodland. The first point, at 1846, is an estimate of original organic C content on all plots. Dotted lines are shown only to improve clarity.

ment whilst levels have remained stable on plots receiving no fertilization. Plots receiving inorganic fertilizers only have shown very little change in soil organic C content over the course of the experiment (Jenkinson et al., 1987). In the area allowed to naturally regenerate since 1882, soil organic C contents have trebled.

The information provided by these two experiments could not have been collected in any way other than by long-term experiment.

4. Use of long-term experiments to evaluate and compare SOM models

There are a number of reasons why long-term, rather than short-term, experiments are needed for SOM model evaluation in the context of global environmental change. Firstly, small changes in SOM content are difficult to measure accurately over short periods, because of year-to-year variation in crop growth, and thus inputs of organic matter. Secondly, any changes must be measured against the large background of SOM already present in the soil. Arable topsoils commonly contain 1–3% organic C (approximately 20–50 Mg ha^{-1} in the top 25 cm), with grassland and forest soils often containing more, particularly if poorly drained (Jenkinson, 1988). Thirdly, changes in SOM occur slowly and can only be detected in experiments that have run for more than, say, 20 yr in temperate climates (see Figs. 3 and 4). There are many other examples of this (e.g., Balesdent et al., 1988; Jenkinson, 1988; Johnston, 1991; Körschens, 1994; Schjønning et al., 1994). In tropical climates, or where drastic alterations in land-use have occurred, changes may be measurable over shorter periods.

In this section, we present an example of how long-term experiments can be used to evaluate SOM models by taking two treatments from the Bad Lauchstädt Static Fertilizer Experiment (the high fertilization and no fertilization treatments) and evaluating the performance of two SOM models in simulating soil organic C dynamics over a 40 yr period. The two models which we compare are the Rothamsted Carbon Model (RothC; Coleman and Jenkinson, 1996) and CANDY (Franko, 1996). The results presented here form part of a much larger model evaluation and comparison exercise (nine models across twelve long-term data-sets) begun at a NATO Advanced Research Workshop

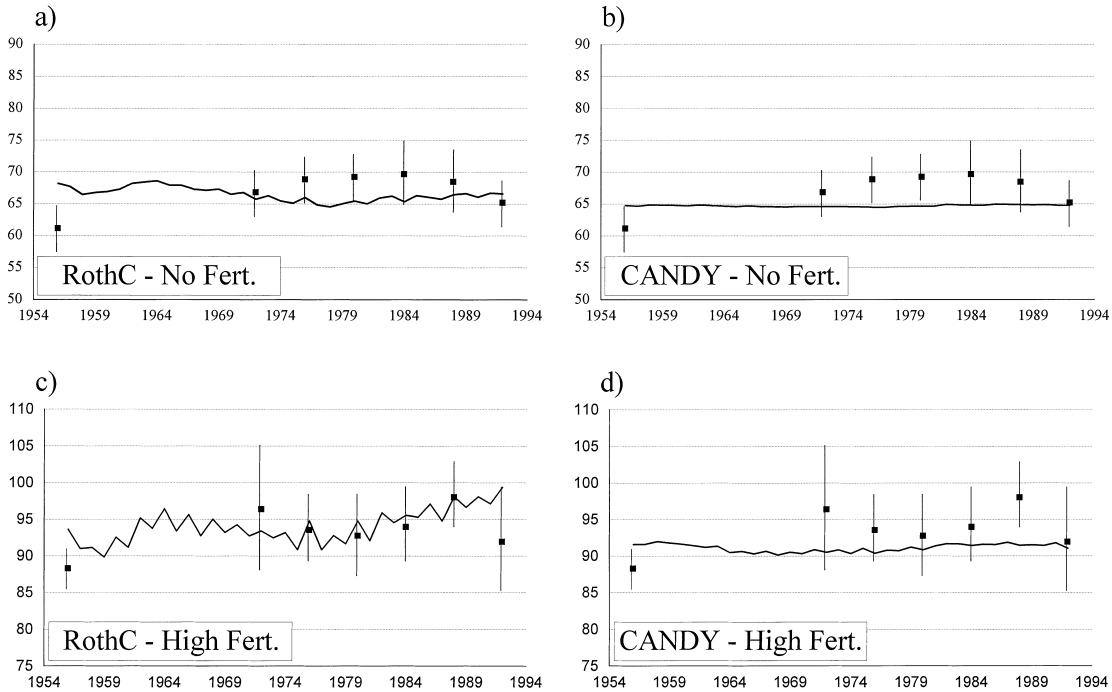

Fig. 5. The performance of the models RothC and CANDY when simulating changes in organic C content (Mg ha^{-1}) in the top 30 cm of soil in the Bad Lauchstädt Static Fertilizer Experiment during the past 40 yr. Simulations are shown as a line whilst measured data are shown by ■. Standard error bars for the measurements are shown. (a) RothC's simulation of the no fertilizer treatment, (b) CANDY's simulation of the no fertilizer treatment, (c) RothC's simulation of the high fertilizer treatment, and (d) CANDY's simulation of the high fertilizer treatment.

held at IACR-Rothamsted in 1995. The full comparison is reported in Smith et al. (1998d). Fig. 5 shows the simulations of the two treatments from the Static Fertilizer Experiment as produced by RothC and CANDY.

The performance of each model can be quantified (see Smith et al., 1996). Table 1 provides statistics describing the performance of the models in simulating these two treatments.

As seen from Fig. 5, and from the statistics in Table 1, both models simulated the measured data very well. Both RothC and CANDY produced simulation lines that were within the standard error of most of the measured data. The close model fit was reflected in the statistics. The root mean square error, RMSE, values for the no fertilization treatment were between 5 and 6 which is less than the $RMSE_{95\%}$ value for this data of 13.98, indicating that the simulations fell within the 95% confidence interval of the measured data. Similarly, the RMSE values of between 3 and 5 for the high fertilization treatment were well below the $RMSE_{95\%}$ value of 16.66. The values for coefficient of determination, CD, were all above 1 and indicate that the deviation of the simulated values from the mean of

Table 1
Statistics describing aspects of the performance of the RothC and CANDY models when simulating data from the Bad Lauchstädt Experiment

Statistic	RothC No Fert.	RothC High Fert.	CANDY No Fert.	CANDY High Fert.
Root mean square error, RMSE	5.75	3.51	5.42	4.23
Coefficient of determination, CD	3.87	1.49	1.48	1.31
Relative error, E	1.23	−1.60	3.25	2.55
Number of paired values	7	7	7	7

the measured values, is less than the deviation of the measured data from their mean value.

A significant bias in a given simulation would be indicated by a relative error, E, greater than the $E_{95\%}$ value which for the no fertilization data was 13.61, and for the high fertilization data was 15.79. The close match between the simulation lines and the measured data was again reflected in low values for E which were all well below the respective $E_{95\%}$ values, suggesting that was no significant bias towards either over- or under-prediction by either model.

Both models then performed well when simulating both treatments from the Static Fertilizer Experiment. The examples presented in this section demonstrate the value of long-term experiments in evaluating SOM models. A more comprehensive evaluation of SOM models using long-term data is presented in Smith et al. (1998b, d).

5. Potential for C sequestration in European agricultural soils – rough estimates using our two examples

The IPCC identifies three main C mitigation options for agriculture: (a) reduction of agriculturally-related emissions (e.g., reduced tillage, less intensive production), (b) use of biofuels to replace fossil fuels (which also increases C in the standing woody biomass and can increase soil C sequestration), and (c) the sequestration of C in soils (e.g., by afforestation or amendment with organic inputs; IPCC, 1996). It is the latter option that we examine here.

Agricultural soils contain far less organic matter than many other soils. For example, 70–80% of soil organic C in the UK is contained in peats, mainly in Scotland (Howard et al., 1995) and 47% of the total C in European soils is held within high organic matter soils (≥8% o.m.) that cover only 13% of Europe's area (see Table 2). Many of these high C content soils are not used intensively for agriculture, although planting of trees on upland peats is an issue in some areas. It is vital to minimise release of C from high C soils through careful management. However, despite the relatively low C content of agricultural soils, the greatest potential to *increase* current soil C stocks is through manipulation of agricultural land, particularly land under arable crops.

There are many opportunities for such manipulation within Europe and North America with agricultural overproduction currently dealt with through policies such as set-aside (Europe) and the Conservation Reserve Program (USA). It is projected that by 2010, 20–30% of land currently under crops in Europe will be surplus to agricultural requirements (Flaig and Mohr, 1994).

In this section, using simple calculations based upon our two case studies from long-term experi-

Table 2
Calculation of total C in European topsoils (0–30 cm)

% SOM in top 30 cm of soil	% C in top 30 cm of soil [a]	Soil bulk density ($Mg\ m^{-3}$) [b]	C ($Mg\ ha^{-1}$) in top 30 cm of soil	% of area of Europe with this SOM content [c]	Area of Europe ($\times 10^6$ ha)	Total C in that soil type in Europe ($\times 10^9$ Mg)
1	0.58	1.45	25.23	28.48	139.32	3.51
2	1.16	1.26	43.82	10.72	52.44	2.30
3	1.74	1.15	59.91	20.87	102.09	6.12
4	2.32	1.07	74.37	18.51	90.54	6.73
5	2.9	1.01	87.63	10.17	49.75	4.36
8	4.64	0.88	122.21	3.84	18.78	2.30
10	5.8	0.82	142.09	2.08	10.17	1.45
14	8.12	0.72	176.38	3.24	15.85	2.80
30	17.4	0.51	268.55	3.87	18.93	5.08
			Totals:	101.78	497.86	34.64

[a] Assuming C to comprise 58% of SOM (Fraters et al., 1993).
[b] From equation relating SOC to soil bulk density in Howard et al. (1995).
[c] Calculated by adding % areas of all soil types with same % SOM content (Fraters et al., 1993); note sum of % area values is greater than 100% due to rounding errors.

ments, we make rough estimates of the potential for C sequestration in European agricultural soils in two scenarios. The two scenarios examined here are (a) the amendment of all arable soils in Europe with 10 Mg ha^{-1} yr^{-1} of organic manure, and (b) the afforestation of surplus arable cropland. All calculations are subject to many simplifications and assumptions which are discussed below as they occur.

5.1. Deriving values for the current C status of soils in Europe

This subsection briefly describes the derivation of soil C stocks in the various portions of land used in the calculations. The total area of Europe (all calculations exclude the most of the former Soviet Union except for Belorus and the Ukraine) is taken as 489×10^6 ha (UNCS/ECE, 1987), and the area of Europe in agricultural use (for the 1980s) is taken as 255×10^6 ha (UNCS/ECE, 1987). These areas were used with estimates of the total C content of European topsoils (0–30 cm), calculated from the percentage of European soil types with different percentage SOM contents (in top 30 cm of soil) as used in the construction of the Soil Organic Matter Map of Europe (derived from data in Fraters et al., 1993). Though some C will reside in soil below 30 cm, we use a 30 cm depth since this will contain most of the C potentially affected by agricultural practices. Details are given in Table 2. By adding the values in the last column of Table 2 we derive a value for the total C present in European soils (0–30 cm) of 3.464×10^{10} t $= 34.64\times10^{15}$ g $=$ 34.64 Pg.

Both of the scenarios presented in this section involve manipulation of surplus arable land. Soils with very high organic C content mostly occur in natural ecosystems and will not normally be under arable cultivation. Instead, arable agriculture is likely to occur on soils with lower SOM content. Let us assume that arable agriculture only occurs on soils $\leq$5% SOM, which is equivalent to 2.9% organic C content. Soils with high SOM ($\geq$8%) that cover 13% of Europe's area and contain 35% of Europe's total C stock, will therefore remain unaffected by the manipulations presented in these scenarios. The soils that could support arable agriculture (i.e., $\leq$5% SOM) collectively cover an area of 434×10^6 ha and contain 23.02 Pg C to a depth of 30 cm (Table 2).

The area of land in agricultural use (arable land, grassland and permanent crops such as vines etc.) in Europe is 255×10^6 ha. Of this, 135×10^6 ha is in arable use (UNCS/ECE, 1987). The 434×10^6 ha of land with SOM $\leq$5% that could support arable agriculture contains 23.02 Pg C, thus the 135×10^6 ha actually in arable use contains 7.18 Pg C.

Having derived these values we are now in a position to make simple calculations based upon our two case studies.

5.2. Scenario one – amendment of all arable soils in Europe with 10 mg ha^{-1} yr^{-1} organic manure

We examine a scenario whereby all arable soils are amended with organic manure in order to increase their organic C content. We assume that enough organic manure will be available, that no land currently receives organic amendments, and we ignore the possible effects on land use of producing this level of manure (e.g., greater requirement for grazing land etc.). For now, we also ignore potential environmental side-effects such as increased risk of nitrate leaching or trace gas fluxes from the soil, and consider only the effect on soil C. Our aim is to establish an upper limit for C sequestration that could be obtained under ideal conditions using agronomically realistic application rates.

In one of our case studies, the Broadbalk Wheat Experiment, amendments to the soil of 35 Mg ha^{-1} yr^{-1} organic manure (as Mg ha^{-1} of farm yard manure has been added to one plot every 2 yr (equivalent to 10 Mg ha^{-1} yr^{-1}; Körschens and Müller, 1996). After 90 yr, the organic C content (to 30 cm) of this plot is 80.19 Mg ha^{-1} compared to 65.21 Mg ha^{-1} on the unfertilized plot representing an increase in organic C of about 23% over 90 yr (see Fig. 3).

To use this example, let us assume a similar increase in C content for all arable soils in Europe to that seen at Bad Lauchstädt. The soil C stock in arable soils would be increased by 23% from 7.18 Pg to 8.83 Pg by amendment with 10 Mg ha^{-1} yr^{-1} of organic manure (an increase of 1.65 Pg over 90 yr).

Over 90 yr this would lead to an increase in the soil C content for Europe as a whole of 4.76% [i.e., increasing the total C content from 34.64 Pg (Table 2) to 36.29 Pg]. This corresponds to an increase in total C content in Europe of about 0.05% yr^{-1} which is equivalent to a rate of increase in total C stock in European soils of 18.33 Tg yr^{-1}.

5.3. Scenario two – afforestation of arable land in Europe that will be surplus to agricultural requirements in 2010

In this scenario we first assume that surplus arable land is allowed to revert to natural woodland. In one of our case studies, the afforestation of a portion of the Broadbalk Wheat Experiment by natural regeneration (Broadbalk Wilderness) led to an increase in soil C content from about 20 to 60 Mg ha^{-1}, i.e., 40 Mg C ha^{-1} over about 100 yr (Jenkinson, 1990; see Fig. 4). This corresponds to an increase in total C of about 200% over 100 yr (higher than that found at the nearby Geescroft Wilderness site; Poulton, 1996).

The total C stock for arable soils in Europe (0–30 cm) was estimated previously at 7.18 Pg, so for 20–30% of this land (an area of $27.1–40.6 \times 10^6$ ha) a total C content of 1.44–2.15 Pg is derived. If we assume a similar increase in C content for all arable soils in the afforested area as the change that occurred in Broadbalk Wilderness, the soil C stock in the afforested area would increase from 1.44 to 4.32 Pg (an increase of 2.88 Pg) for 20% afforestation, or from 2.15 to 6.45 Pg (an increase of 4.3 Pg) for 30% afforestation, over 100 yr.

Assuming 20% afforestation, over 100 yr this would lead to an increase in soil C content for Europe as a whole of 8.31% [i.e., increasing the total C content from 34.64 Pg (Table 2) to 37.52 Pg]. This corresponds to an increase in total C content in Europe of about 0.08% yr^{-1} which is equivalent to a rate of increase in total C stock in European soils of 28.8 Tg yr^{-1}. If one considers that standing woody biomass contains approximately three times the amount of C than does the soil under natural regeneration (Jenkinson, 1971), the total value (i.e., the value including medium term C storage in woody biomass) for C sequestration in Europe by afforesting 20% of current arable land is 115.2 Tg yr^{-1} (equivalent to about 33.26% over 100 yr, or 0.33% yr^{-1}). Carbon sequestered in woody biomass is, however, sequestered only temporarily unless utilised as durable bioproducts (Carter and Hall, 1995).

Similar calculations assuming that 30% of current arable land is afforested indicate an increase of 4.3 Pg or 12.41% of current C stocks over 100 yr, which is equivalent to 43 Tg C yr^{-1} or 0.12% yr^{-1}. Corresponding values including temporary storage in woody biomass are 17.2 Pg or 49.65% of current C stocks over 100 yr, which is equivalent to 172 Tg C yr^{-1} or 0.497% yr^{-1}.

These values do not take account of the C mitigation potential of this scenario afforded by the substitution of fossil fuel burning by the use of the woody biomass as biofuel. If included, estimates of the total C stored in woody biomass could be replaced with a fossil fuel substitution factor (see Smith et al., 1997b).

6. Discussion

The amendment of arable soils with organic manures could lead to an approximate soil C sequestration of 18.33 Tg C yr^{-1}, this being equivalent to an increase (over about a century) of 4.76% of present C in the top 30 cm of European soils. The afforestation of 30% of surplus European arable land could lead to a soil C sequestration of 43 Tg C yr^{-1} or 12.41% of current C stocks over a century. Corresponding values including temporary storage in woody biomass are 172 Tg C yr^{-1} sequestered, or an increase of 49.65% of current C stocks, over a century.

The organic manure scenario showed potential for sequestering small amounts of C. Although it may be less realistic as a C mitigation option than the afforestation, this does not, of course, mean that there are not other benefits from the greater, or more efficient, use of manures. These values simply show that the potential for C sequestration is small relative to other options.

The afforestation scenario appears to show the greatest potential for C sequestration in European agricultural soils, supporting previous qualitative assessments (Carter and Hall, 1995), especially if the upper value of 30% surplus arable land by 2010 is assumed. Given other possible benefits of biofuel production to replace fossil fuel and the potential to improve wildlife habitats and landscape appearance, afforestation of surplus arable land is an attractive option. It should be noted, however, that the option of taking 20% to 30% of arable land out of production relies on the continued intensive agricultural use of the remaining land. Possible environmental impacts of this must be weighed against the benefits of increased areas of forest.

It is generally recognised that globally, the greatest potential for C sequestration is in the tropics (IPCC, 1996). However, the potential for C sequestration in temperate agricultural soils needs to be considered. It is estimated that between 400 and 800 Tg C yr^{-1} could be sequestered in agricultural soils globally (IPCC, 1996). The value of 43 Tg C yr^{-1} derived from our 30% afforestation scenario shows that although Europe forms only a small percentage of global land area, there is some potential for sequestering C in European agricultural soils.

To put the values for C sequestration in context, global anthropogenic carbon dioxide-C production in 1991 was 6188 Tg C yr^{-1} (Marland et al., 1994). For Europe, excluding the former Soviet Union, the value is 1126 Tg C yr^{-1} (calculated from values in Marland et al., 1994). Our 30% afforestation scenario sequestered about 43 Tg C yr^{-1}. This is equivalent to 3.8% of annual CO_2–C emissions in Europe. If temporary C storage in woody biomass is included, the value increases to 15.3% of anthropogenic CO_2–C emissions from Europe. Globally this accounts for about 2.8% of anthropogenic CO_2–C emissions. Considering that this is a single scenario confined to manipulation of surplus arable land in a region accounting for only 3.7% of the world's land area (Houghton et al., 1983), the level of potential sequestration is impressive, especially when considering the impact on C emitted from the same land-area.

There is a need to balance advantages of changes in land-use and practice with potential disadvantages by considering such factors as suitability for wildlife habitats, enhancement of landscape appearance, management of wetland buffer zones to protect rivers etc. Soil organic matter accumulation, and hence C storage, is just one of many considerations but needs to be quantified further, not least because of governmental responsibilities to produce inventories of greenhouse gases.

The estimates made here are crude. To refine these estimates it is necessary to perform a more detailed analysis taking account of actual distributions of land-use with respect to soil type, as well as obtaining better estimates of changes in soil C than those used here (which here were derived from only two long-term experiments). Furthermore, we have taken no account here of potential reductions in agricultural emissions and the use of biofuel crops. The European site network provides an excellent resource for refining our estimates, and work has recently been completed (Smith et al., 1997a, b) which built upon the simple calculations presented here and examined more detailed scenarios (including deintensification, e.g., incorporation of pastures in rotations). Refined esitimates of the C sequestration potentials presented here, and estimates for other scenarios are presented in Smith et al. (1997a, b).

Future approaches will inevitably involve simulation modelling to establish the relative potentials for C sequestration under different combinations of soil type and land-use and in different countries/regions within Europe, but it is essential that models are first evaluated to assess their suitability for this task (e.g., Smith et al., 1998b).

7. Concluding remarks

In this paper, we have described the GCTE Soil Organic Matter Network and taken two examples of long-term experiments selected from the European site network to demonstrate how site networks can be used to (a) describe changes in SOM over time, (b) evaluate and compare SOM models, and (c) make rough estimates of the potential for C sequestration in European Agricultural soils. There are many other examples of how site networks can be used to perform regional analyses for a variety of purposes (e.g., Grace, 1996; Körschens, 1996; Paustian et al., 1996; Smith et al., 1997a, b). In all cases, the information that can be gained from a network of sites is greater than the sum of its constituent parts.

In the last section of this paper we used our case examples to make rough estimates of the potential for C sequestration in European agricultural soils. The approach is crude but similar approaches have been used to estimate the potential effects of other land-use changes, e.g., those following the UK Bovine Spongiform Encephalopathy (BSE) crisis (Smith et al., 1996c). At least one scenario investigated suggested that there may be some potential for sequestering useful amounts of C. The European site network provides an excellent resource for refining these estimates by establishing more robust relationships between land-use changes or different management practices and soil organic matter dynamics (e.g., Smith et al., 1997a, b).

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