Using Long-term Experiments to Estimate the Potential for Carbon Sequestration at the Regional Level: An Examination of Five European Scenarios

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Introduction

The Intergovernmental Panel on Climate Change (IPCC) identifies three main carbon (C) mitigation options for agriculture: a) reduction of agriculturally-related emissions, b) use of biofuels to replace fossil fuels, and c) the sequestration of C in soils (IPCC, 1996). In this paper we concentrate on the latter option in Europe.

Recently, a number of studies have been published that use either carbon/ecosystem models and spatial databases (e.g. LEE et al., 1993; DONIGAN et al., 1994) or simple calculations (GUPTA & RAO, 1994) to estimate the potential for C sequestration in various regions.

We have previously outlined the methodology by which results from long-term experiments can be used to assess the potential for C sequestration in soils. We used two long-term experiments to demonstrate how the potential for C sequestration, assuming various scenarios, can be estimated (POWLSON et al., 1996). We have since refined this methodology by establishing robust statistical relationships between various agricultural management practices and long-term changes in soil organic carbon (SOC) content using long-term experiments in Europe. We have used these relationships to examine five scenarios for C sequestration in the European Union (SMITH et al., 1996a).

In this paper we use the relationships derived in SMITH et al. (1996c) to examine the potential for C sequestration in the wider Europe (all Europe excluding most of the former Soviet Union but including Byelorussia and the Ukraine) over 100 years.

Agricultural soils contain far less organic matter than do many other soils. For example, 70-80% of SOC in the UK is contained in peats, mainly in Scotland (HOWARD et al., 1995) and 35% of the total C in European soils is held within high organic matter soils (≥ 8% organic matter; o.m.) that cover only

13% of the area of Europe (POWLSON et al., 1996; SMITH et al., 1996c). 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: the associated drainage and disturbance can lead to significant losses of C.

It is vital to minimize 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 cropland. There are many opportunities for such manipulation within Europe and North America with agricultural overproduction currently dealt with through policies such as set-aside and the Conservation Reserve Program. Some projections indicate that by 2010, 20-30% of current cropland in Europe will be surplus to agricultural requirements (FLAIG & MOHR, 1994).

Materials and Methods

POWLSON et al. (1996) used figures from HOUGHTON et al. (1983) and FRATERS et al. (1993) to derive values for the total C stock of Europe, and of various portions of land within it (see Table 1).

SMITH et al. (1996c) used European long-term experiments selected from the Global Change and Terrestrial Ecosystems (GCTE) global Soil Organic Matter Network (SOMNET) database (SMITH et al., 1996a,b) to derive relationships between various agricultural practices and changes in SOC content of agricultural soils. The relationships derived by SMITH et al. (1996c) are used here to explore five scenarios for sequestering C in soils in Europe namely, a) the amendment of arable soils with animal manure (first examined in

Table 1

Area and SOC content of soils under different land-use in Europe

	Total Europe	**of which land with o.m. content <5%** [2]	**of which utilized agricul-tural area**	**of which arable land**	**of which cereal land**
Area (10^3 ha)	489168 [1]	434137 [2]	254989 [1]	135400 [1]	64977 [3]
SOC content (Pg) [2]	34.64	23.02	13.52	7.18	3.45

[1] Areas from UNSC/ECE (1987),
[2] Calculated in POWLSON et al. (1996),
[3] Assuming same distribution as in European Union (EUROSTAT, 1995)

POWLSON et al., 1996), b) the amendment of arable soils with sewage sludge, c) the incorporation of cereal straw into the soils in which it was grown, d) the afforestation of surplus arable land through natural woodland regeneration (first examined in POWLSON et al., 1996), and e) extensification of agriculture through ley-arable farming.

Potential environmental side-effects, such as increased risk of nitrate leaching or trace gas fluxes from the soil are ignored as are the economic and policy implications of the changes in land management. Only the effect on soil C was considered. Our aim was to establish an upper limit for C sequestration that could be obtained under ideal conditions using agronomically realistic practices.

Results

Amendment of arable soils with animal manure

In this scenario, all arable soils are amended with organic manure at an agriculturally realistic application rate, i. e. 10 t ha^{-1} y^{-1}, in order to increase SOC content and to reduce, to an extent, the amount of inorganic fertilizers required. It is assumed that the current disposal of animal manure to arable land has not decreased the capacity of soils to continue to accumulate SOC. Long-term experiments suggest that this is not an unreasonable assumption. For example, after 144 years of very large annual applications of animal manure (35 t ha^{-1} y^{-1}), SOC content is still increasing on the Broadbalk Wheat Experiment (JENKINSON, 1990). It is assumed that if animal manure is not incorporated into arable soil much of the carbon will be lost from the terrestrial pool through more rapid decomposition. Furthermore, addition to soil under long-term grassland is regarded as a less desirable option as such soils are likely to already have a high carbon content, so the potential for further increase is more limited than in arable soils. We ignore all possible problems (economic, logistical etc.) of moving manure from where it is produced to where it is spread. We also take no account of any changes in farming practice that would be required or of the relative merits of alternative uses of manure such as biogas production.

SMITH et al. (1996c) used seventeen treatments from fourteen long-term experiments to derive a highly significant linear relationship ($r^2 = 0.4851$, $t_{15} = 3.76$, p [two-tailed] = 0.0017) between the amount of animal manure added to the soil and the yearly change in SOC content, despite very different soil types, rotations, climatic conditions and durations of experiment. This relationship was used here to explore the effect of amending all arable soils in Europe with organic manure at 10 t ha^{-1} y^{-1}. From the regression, this was predicted to increase SOC content by 0.326 % y^{-1}. Table 2 shows the changes that would occur if arable soils were amended with animal manure.

Table 2
Amendment of arable soils with animal manure

Amend-ment rate ($t\ ha^{-1}\ y^{-1}$)	% of arable land covered	Increase in SOC in arable land over 100 years (Pg)	Increase in SOC in total European soil over 100 years (Pg)	% increase in SOC in total Europe over 100 years	Yearly increase in SOC ($Tg\ y^{-1}$)
10	>100 [1]	2.34	34.64 → 36.98	6.8	23.41

[1] SMITH et al. (1996c) calculated that the amount of animal manure produced in the European Union could cover all arable land in the European Union at 10 t ha^{-1} y^{-1} with some spare for other uses. We assume a similar case for the wider Europe.

An amendment rate of 10 t ha^{-1} animal manure to all arable soils would increase total SOC stocks in Europe by 6.8% over 100 years (Table 2). Based on estimates of the quantity of manure available in the European Union, an application rate of 10 t ha^{-1} y^{-1} to all arable land is possible and would use 89% of that produced (SMITH et al., 1996c).

Amendment of arable soils with sewage sludge

In this scenario, arable soils are amended with sewage sludge at a realistic application rate in order to increase SOC content. SMITH et al. (1996c) assessed the effect of two rates in the European Union. The lower rate, 1 t ha^{-1} y^{-1} covered a larger area, had the greatest effect on total C stocks and was regarded least likely to result in adverse environmental effects such as organic contaminant or heavy metal pollution (SAUERBECK, 1987; WILLIAMS, 1988; DIRKZWAGER & L'HERMITE, 1989; HALL et al., 1992). Our calculations assume a similar distribution of sewage sludge production in the wider Europe as that found in the European Union, and that 100% of it is recycled to arable land over the next century.

SMITH et al. (1996c) used five treatments from three European long-term field experiments to derive a highly significant linear relationship ($r^2 = 0.9754$, $t_3 = 10.91$, p [two-tailed] = 0.0004) between the amount of sewage sludge added to the soil each year and the yearly change in SOC content. This relationship was used here to explore the effect of amending arable land with sewage sludge. From the regression equation, amendments of soil with sewage sludge at 1 t ha^{-1} y^{-1} increased SOC content by 1.96 % y^{-1}. Table 3 shows the changes that would occur if arable soils were amended with sewage sludge.

An application rate of 1 t ha^{-1} y^{-1} increases total SOC content by 4.5% over 100 years (Table 3).

Table 3
Amendment of arable soils with sewage sludge

Amendment rate ($t\ ha^{-1}\ y^{-1}$)	% of arable land covered	Increase in SOC in arable land over 100 years (Pg)	Increase in SOC in total European soil over 100 years (Pg)	% increase in SOC in total Europe over 100 years	Yearly increase in SOC ($Tg\ y^{-1}$)
1	11.17 [1]	1.57	34.64 → 36.21	4.5	15.72

[1] SMITH et al. (1996c) calculated that the amount of sewage sludge produced in the European Union could cover 11.17% of arable land in the European Union at 1 $t\ ha^{-1}\ y^{-1}$. We assume a similar case for the wider Europe.

Incorporation of cereal straw into the soils in which it was grown

In this scenario, cereal straw is ploughed back into the soils in which it was grown. The rate of straw incorporation is 5.07 $t\ ha^{-1}\ y^{-1}$ to all cereal land (see footnote 1; Table 4). This scenario is mutually exclusive to the animal manure amendment scenario since cereal straw used as livestock bedding is essential for farmyard manure production.

SMITH et al. (1996c) used ten treatments from eight European long-term field experiments to derive a significant linear relationship ($r^2 = 0.4143$, $t_8 = 2.38$, p [two-tailed] = 0.0413) between the amount of straw incorporated into the soil each year and the yearly change in SOC content. This relationship was

Table 4
Incorporation of straw to all cereal land

Incorporation rate ($t\ ha^{-1}\ y^{-1}$) [1]	% of cereal land covered	Increase in SOC in cereal land over 100 years (Pg)	Increase in SOC in total European soil over 100 years (Pg)	% increase in SOC in total Europe over 100 years	Yearly increase in SOC ($Tg\ y^{-1}$)
5.07	100	2.61	34.64 → 37.25	7.5	26.08

[1] SMITH et al. (1996c) calculated the amount of cereal straw produced in the European Union per year and using the area of cereal land calculated that if all straw were incorporated into the cereal land on which it was grown it would provide an incorporation rate of 5.07 $t\ ha^{-1}$. The figure is used assuming a similar distribution of cereal farming in the wider Europe. Percentage cereal land covered is by definition 100%.

used here to explore the scenario of incorporating all cereal straw into cereal land. From the regression equation, incorporation of 5.07 t ha^{-1} y^{-1} increases SOC content by 0.76 % y^{-1}. Table 4 shows the changes that would occur if straw were incorporated into cereal land.

Incorporation of all cereal straw back into the soil in which it was grown would increase total SOC stocks in Europe by 7.5% over 100 years (Table 4).

Afforestation of surplus arable land through natural woodland regeneration

In this scenario, all surplus arable land is allowed to revert to natural woodland over a century. Some projections indicate that 20 to 30% of current arable land in Europe will be surplus to agricultural requirements by 2010 (FLAIG & MOHR, 1994) although in the short-term, set-aside areas have been decreased from 15% to 10% or less. We examine the effect of afforestation of 30% of current arable land by natural woodland regeneration.

Table 5
Afforestation of surplus arable land through natural woodland regeneration

% current arable land afforested	Area of arable land (10^3 ha) [1]	Increase in SOC in afforested area over 100 years (Pg)	Increase in SOC in total European soil over 100 years (Pg)	% increase in SOC in total Europe over 100 years	Yearly increase in SOC (Tg y^{-1})
30	40620	3.58	34.64 → 38.22	10.3	35.78

[1] Area of arable land covered is estimated from figure in Table 1

Using the mean value from the only two natural woodland regeneration long-term experiments in Europe, SMITH et al. (1996c) determined that natural woodland regeneration increases SOC content by 1.66% y^{-1}. This figure was used here to determine the effect on total European SOC of afforesting 30% of current arable land. Table 5 shows the changes that would occur if surplus arable land were allowed to revert to woodland.

Afforestation of 30% of (surplus) arable land would increase total SOC stocks in Europe by 10.3% over 100 years (Table 5). Tree growth also sequesters C in wood. JENKINSON (1971) estimated the C in standing woody biomass to be three times that found in soil on natural woodland regeneration experiments. Standing woody biomass would therefore accumulate 10.74 Pg C over 100 years. This is sequestered only temporarily, however, unless converted to durable bioproducts (CARTER & HALL, 1995) which could extend the period of sequestration. An alternative to the use of wood in bioproducts is to use it to replace fossil fuels in energy production. Although natural woodland regeneration is probably not the most efficient means of woody biofuel production, we can calculate the potential of the wood produced to substitute for fossil fuel. This has the advantage of reducing fossil fuel C emissions. Not all of the C sequestered by trees can be converted to bioproducts or to energy to reduce C emissions. In Table 6 we provide details of the extra C mitigation potential of this scenario if either a) 100% of wood is converted to durable bioproducts, b) 100% of wood is burned for energy production as biofuel, and c) 50% of wood is converted to bioproducts and 50% is burned for energy production.

Table 6

C mitigation potential of wood produced by afforestation of surplus arable land through natural woodland regeneration

C in woody biomass after 100 years (Pg)	Yearly accumulation of C in wood ($Tg\ y^{-1}$)	Use of the wood	Yearly sequestration of C in durable bioproduct ($Tg\ y^{-1}$)	Yearly C emission reduction ($Tg\ y^{-1}$) [1]	Total yearly C mitigation potential ($Tg\ y^{-1}$)
10.73	107.34	100% as bioproducts	107.34	0	107.4
10.73	107.34	100% as biofuel	0	40.25-60.38	40.25-60.38
10.73	107.34	50% as bioproducts, 50% as biofuel	53.67	20.13-30.19	73.8-83.86

[1] Using assumed energy utilization factor of 75% from IPCC (1996) and energy substitution factor (lower and higher) of 0.5-0.75 SAMPSON et al. (1993)

In addition to the 35.78 Tg C y^{-1} sequestered in soil, 100% conversion of wood to bioproducts would result in a further 107.34 Tg C y^{-1} being sequestered, whereas burning all of the wood for energy production would substitute 40.25-60.38 Tg C y^{-1} for fossil fuel C. The combined scenario, whereby 50% of wood is used for durable bioproducts and 50% is used for energy production yields a C mitigation potential of 73.8-83.86 Tg C y^{-1}. Not all wood (small branches, twigs etc.) is suitable for conversion to bioproducts and this will vary according to tree species and period of growth before cropping but the 50:50 scenario of wood use may be more realistic. The lowest estimate of yearly C emission reduction through burning wood for energy is slightly larger than the amount of C sequestered in soil under afforestation. This indicates that the C mitigation potential of the afforestation scenario is more than doubled by including biofuel substitution for fossil fuels in these calculations. A combined strategy of using some wood for durable bioproducts and the rest for energy production could allow the C mitigation potential of the afforestation scenario to be nearly tripled with respect to C sequestration in soil. It is unlikely that this potential could be completely realized. Indeed, it would not necessarily be desirable to do so as it is environmentally advantageous to create or preserve biologically diverse habitats through relatively unmanaged forests.

Agricultural extensification through ley-arable farming

Estimates of the proportion of arable land that will become surplus to agricultural requirements assume the current level of intensive agriculture. An alternative to changing the land-use of surplus arable land is to use the total current arable land in a less intensive way. In this scenario, we assume that food requirements in Europe will remain constant over the next century (the human population is predicted to remain constant at least to 2025; SAUERBECK, 1993) and that the number of animals farmed for meat and other products will not increase (total livestock numbers in the European Union have remained fairly constant over the past 10 years; EUROSTAT, 1995). Current grassland is left in its present form since this is currently sufficient to support the needs of livestock. Cattle farming is not altered in the present scenario. Potential problems regarding the suitability of various soils for ley-arable farming are ignored. The figure for surplus arable land by 2010 (up to 30%) of FLAIG & MOHR (1994) suggests that present arable production could be achieved on 70% of current arable land.

In this scenario, all arable land is put into ley-arable rotation so that at any one time 30% of land is in a ley phase. The ley phase of the rotation (two years in a six year rotation) could then be used to extensify pig and poultry production by moving intensively farmed pigs and poultry to outdoor units. SMITH et al. (1996c) calculated that all intensively farmed pigs and poultry in the European Union could be moved to less intensive outdoor units on the ley phase of ley-arable rotations.

Using the mean value from three European long-term experiments on land formerly under exclusive arable agriculture and a study referring to a further three experiments, SMITH et al. (1996c) determined that ley-arable farming increases SOC content by 1.02% y^{-1}. This figure was used here to determine the effect on total European SOC of converting current arable land to a 1/3 ley-arable system. Table 7 shows the changes that would occur if arable land were converted to ley-arable farming.

Conversion of current arable land to a ley-arable system would increase total SOC stocks in Europe by 21.05% over 100 years (Table 7), the greatest effect on SOC content of any of the scenarios examined in this paper.

Table 7

Agricultural extensification through ley-arable farming

% current arable land put into ley-arable	Increase in SOC in arable land over 100 years (Pg)	Increase in SOC in total European soil over 100 years (Pg)	% increase in SOC in total Europe over 100 years	Yearly increase in SOC (Tg y^{-1})
100	7.29	34.64 → 41.93	21.1	72.92

Based on manure production per animal (MAFF, 1994) and stocking densities of 13 ha^{-1} for pigs (MAFF, 1983) and 1000 ha^{-1} for poultry (LAMPKIN, 1990), pigs would add 19.5 t ha^{-1} and poultry would add 31.5 t ha^{-1} animal manure to the leys (SMITH et al., 1996c).

Furthermore, animal manure from cattle production (unaltered in this scenario) could still be used for the arable phase of this system (in the European Union there is enough to amend all land in the arable phase with over 10 t ha^{-1} y^{-1}; SMITH et al., 1996c). Data are not available to assess whether or not this level of manure application to the ley-arable system would further increase SOC content in the soil.

Discussion

It is generally recognized that globally, the greatest potential for C mitigation is in the tropics (e.g. SAUERBECK, 1993). However, the potential for C sequestration in temperate agricultural soils needs to be considered. It is estimated that between 400 and 800 Tg C y^{-1} could be sequestered in agricultural soils globally (IPCC, 1996). The figures of 35.78 Tg y^{-1} for soil sequestration and up to 83.86 Tg y^{-1} for C mitigation potential (assuming 50:50 bioproduct:biofuel use of the wood) in the afforestation scenario show that despite covering only 3.65% of the earth's land area, Europe could potentially contribute about 30% toward the lower global estimate assuming afforestation of 30% of current arable land.

To put the figures for C sequestration in context, global anthropogenic CO_2 production in 1991 was 6188 Tg C y^{-1} (MARLAND et al., 1994). Anthropogenic CO_2-C production in Europe excluding the former Soviet Union can be calculated from values given in MARLAND et al. (1994) as 1127 Tg C y^{-1}. The C mitigation potential of the five scenarios examined is shown in Table 8.

The figures in Table 8 show that the afforestation and extensification scenarios show the greatest potential for C mitigation, and can account for 6.5-10.6% of anthropogenic CO_2-C produced in Europe, or 1.2-1.9% of that produced globally.

Soil organic matter accumulation, and hence C storage, is just one of many environmental considerations when assessing these scenarios. As expected, addition of different sources of organic matter (animal manure, sewage sludge and cereal straw) led to different rates of SOC accumulation (KOLENBRANDER, 1974; VAN DIJK, 1982). However, the addition of any of these organic materials to arable soils has only a small impact on the amount of anthropogenic

Table 8

C mitigation potential of the five scenarios examined

Scenario	Yearly C mitigation potential ($Tg\ y^{-1}$) [1]	% of anthropogenic CO_2-C produced annually in Europe [2]	% of anthropogenic CO_2-C produced annually globally [2]
10 t ha^{-1} y^{-1} animal manure to all arable soils	23.41	2.08	0.38
1 t ha^{-1} y^{-1} sewage sludge to arable soils (11.17% land)	15.72	1.39	0.25
5.07 t ha^{-1} y^{-1} straw incorporated into all cereal land	26.08	2.31	0.42
Afforestation of 30% surplus arable land by natural regeneration	119.64 [3]	10.62	1.93
Conversion of all current arable land to 1/3 ley-arable farming with extensification of pig and poultry farming	72.92	6.47	1.18

[1] From Tables 2, 3, 4, 5, 6 and 7; [2] Calculated from figures in MARLAND et al. (1994); [3] Derived by adding SOC sequestration potential (Table 5) and C mitigation potential of wood-C (Table 6) assuming 50:50 bioproduct:biofuel utilization of the wood, and higher energy substitution factor (0.75) of SAMPSON et al. (1993).

CO_2-C produced in Europe. The figures for C sequestration after animal manure amendment using the relationship derived in SMITH et al. (1996c) are slightly higher than those estimated in POWLSON et al. (1996) using a single long-term experiment.

A combination of organic amendments (i. e. sewage sludge at 1 t ha^{-1} to 11%, and animal manure at 15 t ha^{-1} to 75%, of arable land) could increase the potential for C sequestration slightly.

There are, of course, other benefits from the greater and more efficient use of animal manures (e. g. ARDEN-CLARKE & HODGES, 1988) but it is important to weigh the benefits against potential undesirable side effects such as increased risk of nitrate leaching, trace gas fluxes from the soil, increased use of fuels to apply the amendments, and increased heavy metal and organic pollutant concentrations in the environment. The rates of organic amendment suggested here are low, however, and as such are unlikely to lead to serious environmental side effects but we have not attempted to quantify this.

The latter two scenarios have a larger uncertainty associated with them since they use figures derived from fewer long-term experiments (SMITH et al., 1996c). Based upon this more limited data, both show some potential for sequestering useful amounts of C (Table 8).

The afforestation scenario uses only surplus arable land and has a number of other potential environmental advantages such as enhancement of landscape appearance and the provision of wild-life habitats. A disadvantage is that agricultural production on the remaining land would need to remain at its current intensive level. The figures for C sequestration after afforestation using the figures of SMITH et al. (1996c) are lower than (nearly half) those estimated in POWLSON et al. (1996) using a single long-term experiment.

The extensification scenario, as well as sequestering C, would also yield a number of other potential benefits such as improved animal welfare and decreased requirement for inorganic fertilizers but could increase the risk of nitrate leaching when ley pastures are ploughed under.

Of the five scenarios investigated, the extensification scenario uses the largest number of assumptions. It is also the most reliant upon suitability of soil types and climate (outdoor pig farming is better suited to light soils and mild climate; MAFF, 1983); aspects not considered here.

Conclusions

The estimates of the potential for C sequestration in soils in Europe are based upon the best long-term data available in Europe. Account was not taken in these estimates of the suitability of soils or climate in a given region or of the local availability (or surplus) of resources used (such as animal manure), nor of the potential problems of moving resources from one locality to another. To account for such factors, a more sophisticated approach is required, ideally involving the use of spatial databases of soil, climate, ground cover etc. in Europe coupled with a suitable dynamic simulation model (similar to the approach used by DONIGAN et al., 1994 and LEE et al., 1993).

A model evaluation and comparison exercise (SMITH et al., 1996d) involving nine soil organic matter models and twelve long-term datasets has recently been undertaken to determine the suitability of models for such purposes (SMITH et al., 1996a).

The estimates provided here serve to define only the *potential* for C sequestration in Europe. Given that they may tend to overestimate the level of C sequestration attainable in practice, and given that the scenario with the greatest potential for C mitigation can sequester less than 2% of the annual anthropogenic CO_2-C produced globally, the figures presented in this paper do not contradict the view that, although efforts in temperate agriculture can make small contributions to global C mitigation, more significant impacts can be made by halting tropical and sub-tropical deforestation (SAUERBECK, 1993) and by reducing anthropogenic CO_2 emissions from fossil fuel burning (HOUGHTON et al., 1992).

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