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Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture

PETE SMITH†, DAVID S. POWLSON, JO U. SMITH, PETE FALLOON and KEVIN COLEMAN
Soil Science Department, IACR-Rothamsted, Harpenden, Herts AL5 2JQ, UK

Abstract

Under the Kyoto Protocol, the European Union is committed to a reduction in CO_2 emissions to 92% of baseline (1990) levels during the first commitment period (2008–2012). The Kyoto Protocol allows carbon emissions to be offset by demonstrable removal of carbon from the atmosphere. Thus, land-use/land-management change and forestry activities that are shown to reduce atmospheric CO_2 levels can be included in the Kyoto targets. These activities include afforestation, reforestation and deforestation (article 3.3 of the Kyoto Protocol) and the improved management of agricultural soils (article 3.4). In this paper, we estimate the carbon mitigation potential of various agricultural land-management strategies and examine the consequences of European policy options on carbon mitigation potential, by examining combinations of changes in agricultural land-use/land-management.

We show that no single land-management change in isolation can mitigate all of the carbon needed to meet Europe's climate change commitments, but integrated combinations of land-management strategies show considerable potential for carbon mitigation. Three of the combined scenarios, one of which is an optimal realistic scenario, are by themselves able to meet Europe's emission limitation or reduction commitments.

Through combined land-management scenarios, we show that the most important resource for carbon mitigation in agriculture is the surplus arable land. We conclude that in order to fully exploit the potential of arable land for carbon mitigation, policies will need to be implemented to allow surplus arable land to be put into alternative long-term land-use.

Of all options examined, bioenergy crops show the greatest potential for carbon mitigation. Bioenergy crop production also shows an indefinite mitigation potential compared to other options where the mitigation potential is finite. We suggest that in order to exploit fully the bioenergy option, the infrastructure for bioenergy production needs to be significantly enhanced before the beginning of the first Kyoto commitment period in 2008.

It is not expected that Europe will attempt to meet its climate change commitments solely through changes in agricultural land-use. A reduction in CO_2-carbon emissions will be key to meeting Europe's Kyoto targets, and forestry activities (Kyoto Article 3.3) will play a major role. In this study, however, we demonstrate the considerable potential of changes in agricultural land-use and -management (Kyoto Article 3.4) for carbon mitigation and highlight the policies needed to promote these agricultural activities. As all sources of carbon mitigation will be important in meeting Europe's climate change commitments, agricultural carbon mitigation options should be taken very seriously.

Correspondence: Dr Pete Smith, tel +44/(0)1582-763133 × 2110,
fax +44/(0)1582-769222/ 760981, e-mail pete.smith@bbsrc.ac.uk

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Introduction

Annex B of the Kyoto Protocol (available at: HTTP://www.cop3.de/) lists the Quantified Emission Limitation or Reduction Commitments for 39 of the parties that ratified the United Nations Framework Convention on Climate Change (UNFCCC). The European Union is committed to a reduction in CO_2 emissions to 92% of baseline (1990) levels during the first commitment period (2008–2012).

The Kyoto Protocol allows carbon emissions to be offset by demonstrable removal of carbon from the atmosphere. Thus, land-use/land-management change and forestry activities that are shown to reduce atmospheric CO_2 levels can be included in the Kyoto emission reduction targets. These activities include afforestation, reforestation and deforestation (article 3.3 of the Kyoto Protocol) and the improved management of agricultural soils (article 3.4). In this paper, we concentrate mainly on Kyoto Article 3.4 options, though afforestation of surplus arable land is also considered.

In a recent series of papers (Smith *et al.* 1997a,b; Smith *et al.* 1998a), we presented preliminary estimates of carbon mitigation potential in Europe by using long-term experiments to develop relationships between changes in soil organic carbon (SOC) content and various land-use/land-management changes. These relationships were then used to examine the potential for carbon mitigation in European agriculture by developing six scenarios whereby a single land-use/land-management change was implemented across Europe. In these papers, the mitigation options were not compared to a baseline condition (i.e. the extent of the practice in 1990) since the baseline year was first introduced in the Kyoto Protocol in December 1997, and the various possibilities for combined land-management options were not examined. Some simple combinations of the various carbon mitigation options presented in Smith *et al.* (1997a,b, 1998a) have been reported (e.g. Paustian *et al.* 1997; Nabuurs *et al.* 1999) but none assess carbon mitigation potential relative to a baseline condition, or consider the competition for available land. In this paper we:

1. establish a 1990 baseline for each land-management practice and report estimates for carbon mitigation potential relative to this baseline
2. use updated scenarios and generalize the relationships presented in previous papers to allow them to be applied to any portion of Europe's agricultural area
3. examine the consequences of various European policy options on carbon mitigation potential by examining combinations of changes in agricultural land-use/land-management.

We have recently completed a similar analysis for the UK (Smith *et al.* 2000a)

Methods

Smith *et al.* (1997a, 1998a) provided estimates for CO_2-carbon mitigation for the European Union consisting of 15 member states in 1996 (EUR15 or EU15). Smith *et al.* (1997b, 1998a) provided estimates for geographical Europe, which is all of the European land area as far east as the Baltic States (excluding the former Soviet Union except for Belarus and Ukraine). In this study we consider the same geographical area of Europe examined in Smith *et al.* (1997b). Since the European Union is currently expanding, it is likely that by the first Kyoto commitment period (2008–2012), political Europe will be better represented by the larger geographical area considered by Smith *et al.* (1997b) than the area considered by Smith *et al.* (1997a). As in Smith *et al.* (1997a,b, 1998a) changes in SOC are assessed to a depth of 30 cm. The areas and

Table 1 Area and SOC content (0–30 cm) of soils under different land use in Europe

	Europe	Land with o.m. < 5% [1]	Utilized Agricultural Area	Arable area
Area (10^3 ha)	489 168 [2]	434 137 [1]	254 989 [2]	135 400 [2]
SOC content (Pg) [3]	34.64	23.02	13.52	7.18

[1] Calculated in Powlson *et al.* (1998); [2] Areas from UNSC/ECE & (United Nations Statistical Commission/Economic Commission for Europe) (1987). [3] SOC figures calculated from soil organic matter map of Europe of Fraters *et al.* (1993) (see Smith *et al.* 1997a). Table adapted from Smith *et al.* (1997b).

carbon stocks for the various portions of European land are given in Table 1.

Only changes to arable agricultural land are considered since grassland is already under management conducive to SOC accumulation compared to arable land, and arable land shows the greatest potential for SOC increase. The ploughing under of grassland causes a rapid decrease in SOC that takes many years to recover (e.g. Smith *et al.* 1996a). For this reason, no changes to soils already high in organic matter (> 8% soil organic matter) or those under grassland are included in this study. As in previous papers (Smith *et al.* 1997a,b; 1998a), the logistics of resource redistribution are not considered. Similarly, although scenarios are chosen to minimize the risk of environmental damage (e.g. sewage sludge application rates of $1\,\mathrm{t\,ha^{-1}\,y^{-1}}$), potential environmental side-effects are not considered explicitly.

In the papers of Smith *et al.* (1997a,b, 1998a), we derived statistical relationships between various agricultural land-management practices and changes in SOC using results derived from European long-term experiments contributing to the Global Change and Terrestrial Ecosystems Soil Organic Matter Network (GCTE-SOMNET; Smith *et al.* 1996b,c,d; 1998b). Increases in soil carbon are finite with systems tending toward new equilibria after about 50–100 y, whereby carbon accumulation slows and eventually stops (Smith *et al.* 1997a). The figures we used here are the average yearly accumulation rate over this period. These changes in SOC were then applied to various soil carbon pools under different land-use to examine scenarios for carbon mitigation. The scenarios examined were: the amendment of soil with organic additions (animal manure, sewage sludge and cereal straw, Smith *et al.* 1997a,b); conversion to no-till agriculture (Smith *et al.* 1998a); agricultural extensification (by this we mean de-intensification, Smith *et al.* 1997a,b); and natural woodland regeneration (with varying degrees of biofuel use of the wood, Smith *et al.* 1997a,b).

In the papers of Smith *et al.* (1997a,b, 1998a) the land-management practices considered were assumed to be absent in present agricultural practice. For some scenarios this assumption was entirely safe (e.g. the permanent afforestation of arable set-aside land which, by definition, was not under woodland at the time), whilst for others (e.g. the addition of organic amendments to soils) the assumption was less safe, because some agricultural practices were in use to varying extents in the early 1990s. In this paper we estimate the extent of use of each land-management practice in Europe in 1990 and estimate the effects of changes in the extent of each practice relative to this 1990 baseline.

Various other changes from the relationships used in Smith *et al.* (1997a,b, 1998a) have been made in this study including (a) the use of variable application rates of organic amendments instead of a fixed rate (e.g. animal manure), (b) a revision of the magnitude of the impact of various management changes on SOC (e.g. sewage sludge and natural woodland regeneration), (c) changes in the agricultural land areas assumed to be available for changes in land-use (e.g. a reduction in the predicted level of set-aside by 2010 affecting extensification, natural woodland regeneration and bioenergy production scenarios), and (d) changes in the scenarios themselves (e.g. the inclusion of two separate scenarios for dedicated bioenergy production and natural woodland regeneration, in place of the combined scenarios of Smith *et al.* 1997a,b). Each scenario, and the assumptions and figures underpinning each scenario are described in detail in the Appendix.

Summary of land-management changes

Table 2 summarizes the yearly SOC accumulation rates for each land-management practice as well as the baseline (1990) occurrence of these practices, and the maximum potential area over which these scenarios can be implemented. For the organic amendments, the estimated yearly surplus of each resource is also provided.

Using the figures derived in this section, we applied the land management changes described to the areas and carbon stocks outlined in Tables 1 and 2 to examine the impact of each land-management change in isolation, and in combination with others.

Combined land-management scenarios

For the combined land-management scenarios, no management practice takes place on the same area of land as another (e.g. an area under no-till cannot also undergo straw incorporation or manure addition). The combined scenarios do not therefore combine different practices on the same portion of land; instead, they utilize different management practices on different portions of the available land. Furthermore, some land-management practices require the use of the same portion of land as others, and so are mutually exclusive in a given combined scenario. An example of this is for the use of surplus arable land: agricultural extensification utilizes all of the 10% surplus arable land and so cannot be used in combination with natural woodland regeneration or bioenergy production, since they rely upon exploitation of surplus arable land.

The combined scenarios were formulated on the basis of potential policy decisions in Europe. The first policy decision considered is how to utilize the surplus agricultural land. This land can be used either for agricultural extensification, which would mean that the area was no longer surplus to requirements, or it can be

Table 2 Summary for each land-management practice of SOC accumulation rates, extent of occurrence during the baseline year (1990), and the maximum area to which each land-management practice could be applied

Land-management practice	SOC accumulation rate (% y^{-1})	Area exclusive to this practice in 1990 (10^6ha)	% of arable area exclusive to this practice in 1990 [3]	Maximum area to which the practice could be applied (10^6ha) [4]	% of arable area to which the practice could be applied	Surplus organic resource available each year (10^6 t y^{-1}) [9]
Animal manure [1] (6.1–20 t ha^{-1} y^{-1})	0.14–0.71	0	0	117.26	86.6 [3]	716.9
Sewage sludge (1 t ha^{-1} y^{-1})	0.49	2.44 [3]	1.8	12.32	9.1 [5]	9.8
Cereal straw (2–10 t ha^{-1} y^{-1})	0.42–1.31	11.64 [3]	8.6	66.21	48.9 [6]	132.5
No-till farming	0.73 (plus fossil-fuel C saving) [2]	4.06 [3]	3	117.26	86.6 [3]	–
Agricultural extensification	1.02	0	0	39.13	28.9 [7]	–
Natural woodland regeneration	1.17 (plus above-ground C) [2]	0	0	13.54	10 [8]	–
Bioenergy crop production	1.17 (plus above-ground C) [2]	0	0	13.54	10 [8]	–

[1] Lowest rate of animal manure is 6.1 t ha^{-1} y^{-1} since this is the rate required to cover all available arable land (i.e. 86.6% of arable area; see footnote 3); [2] The main impact of woodland regeneration and bioenergy crop production lies in the production of above-ground carbon. For no-till farming, fossil fuel C savings also need to be added (see text); [3] In this study, areas already under a practice favourable to SOC accumulation in 1990 (see text) were not manipulated. Hence, 13.4% of Europe's arable area remains in the same land-use as in 1990, which leaves a maximum of 86.6% of the arable area for manipulation; [4] Calculated from percentage in column 6; [5] Given the total surplus of sewage sludge produced in Europe each year, this is the maximum area covered at 1 t ha^{-1} y^{-1}; [6] Given the surplus of straw produced in Europe each year, this is the maximum area covered at the highest incorporation rate (10 t ha^{-1} y^{-1}); [7] The 10% surplus arable land will allow 1/3 of current conventional agriculture to be extensified (see text). Hence, the maximum area available for extensification is 1/3 of the 86.6% arable area available for manipulation; [8] Since these land-management changes are applied exclusively on surplus arable land, the maximum area available for these changes is 10% of arable land; [9] See text for details of how these figures were derived.

used for bioenergy production or woodland regeneration. This first policy decision divides the combined scenarios into three groups that we term 'bioenergy', ''woodland' and 'extensification'. The second policy decision considered relates to how the remaining agricultural land is managed. Potential policies include those encouraging no-till farming, straw incorporation, or the more efficient use of organic amendments (such as animal manure and sewage sludge). On the basis of these different policy decisions, we examined 12 combined land-management scenarios, and one other which is considered to be an optimal realistic scenario. In all scenarios, the area under a practice favourable to carbon accumulation in the baseline year remained unaltered. The policy aims and resulting combined land-management scenarios are shown in Table 3.

Results

The carbon mitigation potential of each land-management change

Relationships were derived between the carbon mitigation potential of each land management practice, and the proportion of arable area to which it was applied. These relationships are given in Table 4.

These relationships were used, with estimates of the maximum area to which the practices could be applied, to derive the maximum yearly carbon mitigation potential for each land-management practice in isolation. Figure 1 shows these values and compares them to the 1990 CO_2-carbon emissions from Europe.

The carbon mitigation potential of combined land-use/land-management scenarios

Using the figure derived above, it was also possible to assess the carbon mitigation potential of various combined land-management scenarios (see Table 3). In all scenarios, the area under a practice favourable to carbon accumulation in the baseline year remained unaltered. Therefore, all scenarios have 13.4% of arable land remaining in 1990 land-use. Tables 5, 6, 7 and 8 show the carbon mitigation potential for each of the combined land-management scenarios outlined in Table 3.

The total carbon mitigation potential for each scenario and the comparison of these figures to 1990 CO_2-carbon emissions from Europe is summarized in Fig. 2.

Table 3 Potential policy decisions and resulting combined land-management scenarios

Policy aim for 10% surplus arable land	Policy aim for remaining arable land	Resulting combined land management scenario	Scenario Abbreviation
Encourage Bioenergy (B)	Encourage no-till (NT)	Bioenergy plus no-till	B + NT
Encourage Bioenergy (B)	Encourage straw incorporation (S)	Bioenergy plus straw incorporation	B + S
Encourage Bioenergy (B)	Encourage organic amendments (O)	Bioenergy plus organic amendments	B + O
Encourage Bioenergy (B)	Encourage organic amendments at highest allowed rates and put remaining area into no-till (O + NT)	Bioenergy plus organic amendments at highest allowed rates and put remaining area into no-till	B + O + NT
Encourage Woodland (W)	Encourage no-till (NT)	Woodland plus no-till	W + NT
Encourage Woodland (W)	Encourage straw incorporation (S)	Woodland plus straw incorporation	W + S
Encourage Woodland (W)	Encourage organic amendments (O)	Woodland plus organic amendments	W + O
Encourage Woodland (W)	Encourage organic amendments at highest allowed rates and put remaining area into no-till (O + NT)	Woodland plus organic amendments at highest allowed rates and put remaining area into no-till	W + O + NT
Encourage Extensification (E)	Encourage no-till (NT)	Extensification plus no-till	E + NT
Encourage Extensification (E)	Encourage straw incorporation (S)	Extensification plus straw incorporation	E + S
Encourage Extensification (E)	Encourage organic amendments (O)	Extensification plus organic amendments	E + O
Encourage Extensification (E)	Encourage organic amendments at highest allowed rates and put remaining area into no-till (O + NT)	Extensification plus organic amendments at highest allowed rates and put remaining area into no-till	E + O + NT
Optimal Realistic Scenario (Opt)	Optimal realistic scenario (Opt)	Use 50% of surplus arable land for bioenergy production and the other 50% for woodland, use organic amendments at the highest rates allowed and put the remaining area into no-till	Opt

Table 4 Relationship between the carbon mitigation potential of each land management practice and the proportion of arable area to which it is applied

Land-management practice	Maximum extra % area of arable land [1]	Maximum yearly carbon mitigation potential for Europe (Tg y^{-1})	Trend-line [5]
Animal manure (at 6.1 t ha^{-1} y^{-1})	86.6	11.10	0.1282
Animal manure (at 20 t ha^{-1} y^{-1})	26.5 *	13.42	0.5070
Sewage sludge (at 1 t ha^{-1} y^{-1})	7.3 *	2.65	0.3630
Cereal straw (at 2 t ha^{-1} y^{-1})	48.9 *	1.09	0.0223
Cereal straw (at 10 t ha^{-1} y^{-1})	9.8 *	6.49	0.6629
No-till farming	86.6	40.40 [2]	0.4665
Agricultural extensification	28.9	21.28	0.7364
Natural woodland regeneration	10	56.05 [3]	4.5202
Bioenergy crop production	10	75.01 [4]	7.5008

[1]This is the area in addition to that already under this land management practice in 1990. Those figures marked with * show the maximum areas covered applying all of the surplus organic material; [2]This figure includes SOC accumulation and fossil fuel carbon savings; [3] This figure includes SOC accumulation and increases in woody biomass carbon.; [4]This figure includes SOC accumulation and carbon mitigation through the substitution of fossil fuel carbon with bioenergy crop carbon; [5]These trend-lines show the carbon mitigation potential per unit area, and are the constants in the equations describing the increase in carbon mitigation potential with increasing area to which the land-management change is applied. All equations have the form: Carbon Mitigation Potential for Europe [Tg y^{-1}] = [trend-line] × percentage arable area to which the land-management change is applied

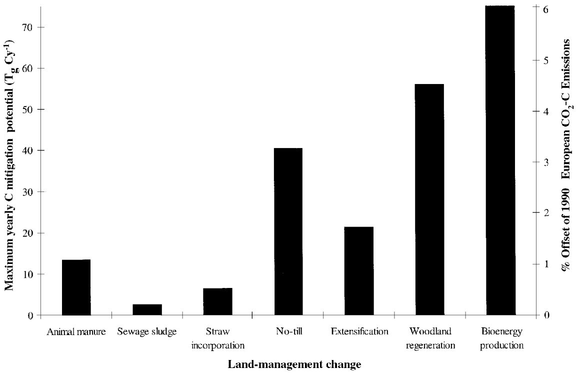

Fig. 1 Maximum yearly carbon mitigation potential, and maximum percentage offset of European 1990 CO_2-carbon emissions, of each land-management practice in isolation. European 1990 CO_2-carbon emissions (1236 TgC y^{-1}) were calculated from figures in Marland *et al.* (1994) as the sum of emissions from Western Europe and Eastern Europe, minus the emissions from the Soviet Union (see Smith *et al.* 1997a,b). Animal manure was applied at 20 t ha^{-1} y^{-1} to 26.5% of arable land. Sewage sludge was applied at 1 t ha^{-1} y^{-1} to an extra 7.3% of arable land (compared to 1990 levels). Straw was incorporated at a rate of 10 t ha^{-1} y^{-1} to an extra 48.9% of arable land (compared to 1990 levels). No-till was applied to all arable land that was not under the same land-management as 1990 (i.e. 86.6% of arable land). Extensification was applied to 1/3 of all arable land not under the same land-management as 1990 (i.e. 28.9% of arable land). Woodland regeneration and bioenergy production were each applied to surplus (i.e. 10%) arable land.

Discussion

Single land-management options

All of the estimates for carbon mitigation potential of single land-management options presented in this study are lower than those reported for the same area by Smith *et al.* (1997b, 1998a). The reasons for these differences are many, but the main difference is the inclusion of a 1990 baseline condition for all scenarios in this study. For each of the organic amendments (manure, sludge and straw), less material was available after accounting for baseline use. For other scenarios, such as woodland regeneration, the SOC accumulation rate was lower and the estimates of above-ground biomass carbon were improved in this study. Only the no-till scenario is close to previous values (Smith *et al.* 1998a) because the only difference from previous estimates was a reduction in the maximum land area available for no-till from 100% to 86.6% of arable land area.

For the scenarios using organic amendments, 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 these. In addition to the potential problems

Table 5 Carbon mitigation potential for combined land-management scenarios, with surplus agricultural land used for bioenergy production (B)

Scenario [1]	Land-management during commitment period	% of arable land used	Carbon mitigation potential
B + NT	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Bioenergy crop C mitigation [2]	10.0	75.01
	Extra No-till [3]	76.6	35.73
	Total		*110.74*
B + S	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Bioenergy crop C mitigation [2]	10.0	75.01
	Extra Straw incorporation (2 t ha^{-1})	48.9	1.09
	Remainder unchanged	27.7	0.00
	Total		*76.10*
B + O	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Bioenergy crop C mitigation [2]	10.0	75.01
	Extra sewage sludge	7.3	2.65
	Animal manure (7.6 t ha^{-1})	69.3	11.77
	Total		*89.43*
B + O + NT	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Bioenergy crop C mitigation [2]	10.0	75.01
	Extra sewage sludge	7.3	2.65
	Animal manure (20 t ha^{-1})	26.5	13.42
	Extra Straw incorporation (10 t ha^{-1})	9.8	6.49
	Extra No-till [3]	33.0	15.39
	Total		*112.96*

[1] See Table 3 for abbreviation code; [2] Includes 56.87 Tg y^{-1} from bioenergy crop C mitigation and 18.14 Tg y^{-1} from SOC accumulation under woody crops; [3] The total carbon mitigation potential for extra no-till of which 93.1% is from SOC accumulation and 6.9% is from fossil fuel carbon savings.

associated with the use of organic materials in agriculture, it is important to consider the additional benefits (e.g. improved soil fertility and structure, and increased agricultural productivity and sustainability; Arden-Clarke & Hodges 1988; Paustian *et al.* 1997; Lal *et al.* 1998) leading, in many cases, to 'win-win' land-management strategies (Lal *et al.* 1998).

It is clear from this study that bioenergy production and woodland regeneration have the greatest potential for carbon mitigation of all land-management options examined. Both rely upon a 10% surplus of arable land. The mitigation potential of the bioenergy scenario (on surplus arable land) is nearly twice that of the best-case mitigation potential on the remaining arable land, which highlights the conclusion that surplus arable land is the most important resource for carbon mitigation in agriculture.

The extra advantage of bioenergy production over all other scenarios is that the fossil fuel carbon substitution component (about 76% of the total carbon mitigation potential) continues indefinitely. In all other scenarios (with the exception of the small fossil-fuel carbon saving from the no-till scenario) the systems tend toward new equilibria after about 50–100 years, whereby carbon accumulation slows and eventually stops.

From Fig. 1, it is clear that no single land-management option can offset all of Europe's 1990 CO_2-carbon emissions. However, it is not appropriate to dismiss mitigation options on the basis that they contribute only small proportions towards the mitigation target (Paustian *et al.* 1997; Royal Society 1999). The finding that no one land-management change in isolation can deliver Europe's climate change commitments highlights the importance of using integrated land management for carbon mitigation.

In attempting in this study to quantify the maximum potential for carbon mitigation through agriculture, no

Table 6 Carbon mitigation potential for combined land-management scenarios, with surplus agricultural land used for woodland (W)

Scenario [1]	Land-management during commitment period	% of arable land used	Carbon mitigation potential
W + NT	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Woodland C accumulation [2]	10.0	56.05
	Extra No-till [3]	76.6	35.73
	Total		*91.78*
W + S	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Woodland C accumulation [2]	10.0	56.05
	Extra Straw incorporation ($2\,\mathrm{t\,ha^{-1}}$)	48.9	1.09
	Remainder unchanged	27.7	0.00
	Total		*57.14*
W + O	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Woodland C accumulation [2]	10.0	56.05
	Extra sewage sludge	7.3	2.65
	Animal manure ($7.6\,\mathrm{t\,ha^{-1}}$)	69.3	11.77
	Total		*70.47*
W + O + NT	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Woodland C accumulation [2]	10.0	56.05
	Extra sewage sludge	7.3	2.65
	Animal manure ($20\,\mathrm{t\,ha^{-1}}$)	26.5	13.42
	Extra Straw incorporation ($10\,\mathrm{t\ ha^{-1}}$)	9.8	6.49
	Extra No-till [3]	33.0	15.39
	Total		*94.00*

[1] See Table 3 for abbreviation code; [2] Includes 37.91 $\mathrm{Tg\,y^{-1}}$ from above-ground carbon accumulation and 18.14 $\mathrm{Tg\,y^{-1}}$ from SOC accumulation under woodland; [3] The total carbon mitigation potential for extra no-till of which 93.1% is from SOC accumulation and 6.9% is from fossil fuel carbon savings.

account was taken 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. In combined land-management scenarios, however, it is easier to select appropriate strategies for given regions since many options are available, each occupying a relatively small percentage of the available arable land area.

Combined land-management options

The use of the surplus arable land is the main factor influencing the efficacy of a combined carbon mitigation strategy. Where the surplus arable land is used to extensify 1/3 of current intensive agricultural production (E + NT, E + S, E + O and E + O + NT scenarios), mitigation potentials of combined scenarios are only about half as effective as scenarios where surplus arable land is used for woodland regeneration or bioenergy production.

When considering the remainder of arable land, scenarios relying upon straw incorporation (B + S, W + S and E + S) perform least well when compared to scenarios with the same use of surplus arable land, followed by those in which low rates of organic amendments are applied (B + O, W + O and E + O). Where no-till is used on large areas (B + NT, W + NT and E + NT), the mitigation potentials are large, but the extent of adoption of no-till (57.7–76.6% extra no-till) in these scenarios is unrealistic within the timeframe before the beginning of the first commitment period in 2008.

A greater carbon mitigation potential, and a more realistic mix of land-management options, arises from the use of no-till on an extra 33% of arable land with the application of all available organic amendments at the highest allowed rates to other portions of arable land

Table 7 Carbon mitigation potential for combined land-management scenarios, with surplus agricultural land used for agricultural extensification of 1/3 of available arable land (E)

Scenario [1]	Land-management during commitment period	% of arable land used	Carbon mitigation potential
E + NT	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Extensification	28.9	21.28
	Extra No till [2]	57.7	26.92
	Total		48.20
E + S	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Extensification	28.9	21.28
	Extra Straw incorporation (2 t ha^{-1})	48.9	1.09
	Remainder unchanged	8.8	0.00
	Total		22.37
E + O	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Extensification	28.9	21.28
	Extra sewage sludge	7.3	2.65
	Animal manure (10.5 t ha^{-1})	50.4	12.50
	Total		36.43
E + O + NT	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Extensification	28.9	21.28
	Extra sewage sludge	7.3	2.65
	Animal manure (20 t ha^{-1})	26.5	13.42
	Extra Straw incorporation (10 t ha^{-1})	9.8	6.49
	Extra No-till [2]	14.1	6.58
	Total		50.42

[1] See Table 3 for abbreviation code; [2] The total carbon mitigation potential for extra no-till of which 93.1% is from SOC accumulation and 6.9% is from fossil-fuel carbon savings.

Table 8 Carbon mitigation potential for the realistic optimal combined land-management scenario (Opt)

Scenario [1]	Land-management during commitment period	% of arable land used	Carbon mitigation potential
Opt	1990 Sewage sludge	1.8	0.00
	1990 Straw incorporation	8.6	0.00
	1990 No-till	3.0	0.00
	Bioenergy crop C mitigation [2]	5.0	37.50
	Woodland regeneration [3]	5.0	28.03
	Extra sewage sludge	7.3	2.65
	Animal manure (20 t ha^{-1})	26.5	13.42
	Extra Straw incorporation (10 t ha^{-1})	9.8	6.49
	Extra No-till [4]	33.0	15.39
	Total		103.48

[1] See Table 3 for abbreviation code; [2] Includes 28.43 Tg y^{-1} from bioenergy crop C mitigation and 9.07 Tg y^{-1} from SOC accumulation under woody crops; [3] Includes 18.96 Tg y^{-1} from above-ground carbon accumulation and 9.07 Tg y^{-1} from SOC accumulation under woodland; [4] The total carbon mitigation potential for extra no-till of which 93.1% is from SOC accumulation and 6.9% is from fossil fuel carbon savings.

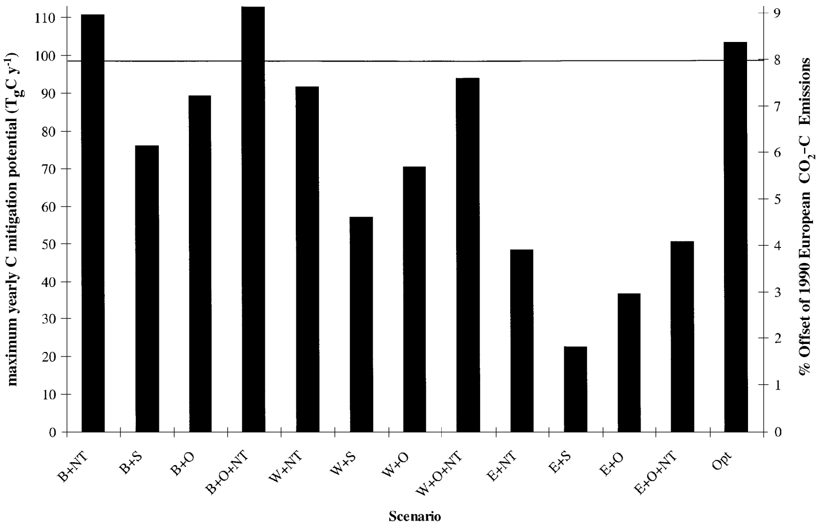

Fig. 2 Maximum yearly carbon mitigation potential, and maximum percentage offset of European 1990 CO_2 emissions of each combined land management scenario. European 1990 CO_2-carbon emissions (1236 Tg C y^{-1}) were calculated from figures in Marland *et al.* (1994) as the sum of emissions from Western Europe and Eastern Europe, minus the emissions from the Soviet Union (see Smith *et al.* 1997a,b). See Table 4 for scenario abbreviation codes. The line at 8% of 1990 CO_2-carbon emissions represents the EU Quantified Emission Limitation or Reduction Commitments for the first commitment period (2008–2012) of the Kyoto Protocol

(B + O + NT, W + O + NT and E + O + NT scenarios). In these scenarios, the application rates for organic amendments are attainable, and the extent of extra no-till farming is not unreasonable. In the USA for example, conservation tillage (no-till, minimum-till and ridge-till) was practiced on 37% of the planted area in 1997 (Lal *et al.* 1998; p57). Of the scenarios with attainable combinations of land-management options, the B + O + NT scenario shows the greatest mitigation potential. It is able, by itself, to offset more CO_2-carbon than the level Europe is committed to in the Kyoto Protocol (though it should be remembered that CO_2-carbon emissions are no longer at 1990 levels). The equivalent scenario where surplus arable land is used for woodland regeneration (W + O + NT) also shows a high carbon mitigation potential (see Fig. 2).

It may not be possible to use all surplus arable land for bioenergy production since it must be sited in close proximity to the bioenergy processing and production plant (Hall *et al.* 1997). If we assume that 50% of surplus arable land could be sited close to bioenergy production plants, the remainder of surplus arable land could be used to grow woodland to maturity. This combined use of surplus arable land is the basis of the realistic optimal realistic scenario (Opt; Table 8). The realistic optimal scenario uses levels of bioenergy production and woodland growth, rates and areas of organic amendment, and an area for no-till farming that are all attainable by the beginning first commitment period (2008). This combined land-management scenario could, by itself, meet Europe's commitments for CO_2-carbon mitigation (Fig. 2).

The realization of the realistic optimal scenario (or similar scenario) would entail changes in European land-management/agricultural policy such that surplus arable land could be put into alternative long-term land-use (instead of short-term rotational set-aside). Additional policies would be required to encourage: (a) bioenergy crop production on surplus arable land where feasible; (b) woodland regeneration on surplus arable land where bioenergy crop production is not feasible; (c) a greater adoption of conservation tillage practices in areas where the land is suitable; and (d) the application of the majority of organic amendments to arable land, with inorganic fertilization replacing current organic fertilization of grassland and nonarable crops. The mechanisms to implement such policies include the use of tax benefits, subsidies, joint implementation projects, and improved extension and information dissemination (Paustian *et al.* 1997).

It is estimated that a net quantity of between 400 and 800 Tg C y^{-1} could be sequestered in agricultural soils globally (IPCC 1996). Our figures, from combined land-management scenarios, show soil carbon sequestration potentials of up to 56 Tg C y^{-1}, which is about 14% of the lower global figure. When above-ground carbon is included, the total carbon mitigation potential is up to 113 Tg C y^{-1}, which is equivalent to about 28% of the lower global figure. This is a significant contribution considering that the geographical area considered here represents only 3.65% of the earth's land surface.

Article 3.3 of the Kyoto Protocol deals with afforestation, reforestation and deforestation. The only forestry activities dealt with in this study relate to woodland regeneration on arable land. Other sources of land for forestry-related carbon mitigation (e.g. under grassland, natural plant cover, or land already under some form of forestry; Nabuurs *et al.* 1999) are outside the scope of this paper. It is likely that these forestry-related activities will also make a significant contribution to European carbon mitigation (Nabuurs *et al.* 1999).

The estimates for carbon mitigation potential presented in this study are based upon a large number of European long-term experiments (Smith *et al.* 1997a; 1998a). Some of the estimates for SOC accumulation rate are based upon statistically robust relationships (e.g. animal manure, sewage sludge, straw incorporation), whilst others are based on fewer experiments and have greater associated uncertainty (e.g. extensification, woodland regeneration, bioenergy production and no-till). Where uncertainty has been estimated for the latter category, the 95% confidence intervals are about 50% of the mean value (Smith *et al.* 1998a). The estimates in this study take no account of differences in soil type and local climate. To improve these estimates, more explicit account needs to be taken of the impact of soil characteristics and local climate on SOC accumulation rates, and on the suitability of different portions of Europe's agricultural land for different land-management options. Dynamic simulation models, coupled to high-quality GIS databases are the ideal tools for such spatially explicit analyses. Further developments include considering the impact of these scenarios on the emission of other greenhouse gases, such as nitrous oxide and methane. We have recently included these gases in our estimates (Smith *et al.* 2000b).

Conclusions

1 The most important resource for carbon mitigation in agriculture is the surplus arable land. In order to fully exploit the potential of arable land for carbon mitigation, policies will need to be implemented to allow surplus arable land to be put into alternative long-term land-use (instead of short-term rotational set-aside).

2 No single land-management change in isolation can mitigate all of the carbon needed to meet Europe's climate change commitments. All carbon mitigation options, even if they contribute only a small proportion towards the mitigation target, need to be considered carefully. Integrated combinations of land-management options show considerable potential for carbon mitigation.

3 Bioenergy crops show the greatest potential for carbon mitigation. Unlike other options, bioenergy crop production also shows an indefinite potential for carbon mitigation. In order to fully exploit the bioenergy option, surplus arable land needs to be made available for longer-term land management changes (see above) and the infrastructure for bioenergy production needs to be significantly enhanced before the beginning of the first Kyoto commitment period in 2008 (Mangan 1997).

4 It is not expected that Europe will attempt to meet its climate change commitments solely through changes in agricultural land-use. A reduction in CO_2-carbon emissions will be key to meeting Europe's Kyoto targets, and forestry activities (Kyoto Article 3.3) will play a major role. In this study, however, we demonstrate the considerable potential of changes in agricultural land-use and -management (Kyoto Article 3.4) for carbon mitigation. We also highlight the policies that would need to be implemented to promote these agricultural activities. Since all sources of carbon mitigation will be important in meeting Europe's climate change commitments, agricultural carbon mitigation options should be taken very seriously.

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Appendix

Animal manure

As a first approximation, Smith *et al.* (1997a,b) assumed that all animal manure produced in Europe was currently used for purposes which did not increase SOC appreciably (e.g. spreading on the surface of grassland; Poulton 1996). It is clear, however, that some animal manure is ploughed into arable land. No figures are available for the extent to which animal manure was spread on arable land in 1990. In order to establish a baseline 1990 level of manure application, we assumed that animal manure was spread evenly upon arable and nonarable agricultural land. From this, the proportion of 'surplus' animal manure (i.e. that not incorporated into arable land and available to further increase SOC in arable land), was calculated.

The arable and nonarable agricultural areas of Europe are 135.4×10^6 ha and 119.6×10^6 ha, respectively (see Smith *et al.* 1997b), giving a fraction of nonarable land (of total agricultural land) of 0.469. The total amount of animal manure produced in Europe each year was calculated by Smith *et al.* (1997b) to be $1529 \times 10^6\,\mathrm{t\,y^{-1}}$. Assuming that animal manure was spread evenly upon arable and nonarable agricultural land, in 1990, 812×10^6 t would have been spread on arable land (an average application rate of $6\,\mathrm{t\,ha^{-1}\,y^{-1}}$ if spread on all arable land) and 717×10^6 t spread on nonarable land. The $717 \times 10^6\,\mathrm{t\,y^{-1}}$ spread on nonarable land would be better employed (for the purposes of increasing SOC; see Poulton 1996) by incorporating into arable land.

In a departure from Smith *et al.* (1997a,b), we used variable application rates of animal manure (those commonly used, e.g. MAFF 1994; between 5 and $20\,\mathrm{t\,ha^{-1}\,y^{-1}}$) in this study to allow different areas to be used in combined land management scenarios. The statistically significant ($r^2 = 0.49$, $t_{15} = 3.76$, $P = 0.0017$) relationship between manure application rate and SOC increase of Smith *et al.* (1997a) was used here following:

$$y = 0.038x – 0.0538,$$

where y = % change in SOC $\mathrm{y^{-1}}$, and x = animal manure added ($\mathrm{t\,ha^{-1}\,y^{-1}}$)

This gives potential SOC accumulation rates ranging from $0.14\%\,\mathrm{y^{-1}}$ (for $5\,\mathrm{t\,ha^{-1}\,y^{-1}}$) to $0.71\%\,\mathrm{y^{-1}}$ (for $20\,\mathrm{t\,ha^{-1}\,y^{-1}}$).

Sewage sludge

The relationship between SOC increase and sewage sludge application at a rate of $1\,\mathrm{t\,ha^{-1}\,y^{-1}}$ used by Smith *et al.* (1997a, 1998a) was based on results from long-term experiments where rates of $6.5\,\mathrm{t\,ha^{-1}\,y^{-1}}$ and above were used. The relationship below $6.5\,\mathrm{t\,ha^{-1}\,y^{-1}}$ was extrapolated to derive SOC changes at $1\,\mathrm{t\,ha^{-1}\,y^{-1}}$ of $1.96\%\,\mathrm{y^{-1}}$. We feel that this is an erroneously large change in SOC. In this paper we have assumed a linear relationship between 0 and $6.5\,\mathrm{t\,ha^{-1}\,y^{-1}}$ to give an SOC accumulation rate of $0.49\%\,\mathrm{y^{-1}}$ at $1\,\mathrm{t\,ha^{-1}\,y^{-1}}$. The application rate of $1\,\mathrm{t\,ha^{-1}\,y^{-1}}$ of sewage sludge was chosen by Smith *et al.* (1997a) because it was considered to be an environmentally safe level (based on the lowest recommended maximum rate in Europe, Williams 1988). Because of this, sewage sludge, unlike straw and animal manure, was always applied at a fixed rate in this study.

The extent to which sewage sludge is applied to arable land varies greatly across Europe with values between 0% (Belgium, Greece) and 90% (Luxembourg) of sewage sludge being applied to agricultural land (including horticulture and gardens; Webber *et al.* 1986). In some countries the amount of sewage sludge applied to arable land will have increased recently, after the 1998 ban on dumping of sewage sludge at sea. From the figures of Webber *et al.* (1986), the amount of sludge applied to agricultural land was calculated. By dividing this figure by the total sludge production, a value for percentage sludge application to agriculture of 38% was derived. The total sludge production for EU15 was calculated to be $8.1 \times 10^6\,\mathrm{t\,y^{-1}}$ by Smith *et al.* (1997a) which is equivalent to $12.3 \times 10^6\,\mathrm{t\,y^{-1}}$ when scaled for the wider Europe considered here (on a population basis assuming similar rates of production in EU and non-EU European countries). We use this value for the baseline total European sewage sludge production in 1990.

Using these figures, $4.7 \times 10^6\,\mathrm{t\,y^{-1}}$ of sewage sludge was applied to agricultural land, of which, $2.5 \times 10^6\,\mathrm{t\,y^{-1}}$ was applied to arable land (assuming that the sludge was spread evenly over all agricultural land). Assuming an application rate of $1\,\mathrm{t\,ha^{-1}\,y^{-1}}$, a maximum arable area of 2.5×10^6 ha would have been treated with sewage sludge which represents 1.8% of European arable land. We use these figures for the 1990 baseline. Given that a calculated $2.5 \times 10^6\,\mathrm{t\,y^{-1}}$ was applied to arable land in the baseline year, an extra $9.8 \times 10^6\,\mathrm{t\,y^{-1}}$ is available for use on arable land. If all the sewage sludge produced in Europe were spread on arable land at an application rate of $1\,\mathrm{t\,ha^{-1}\,y^{-1}}$, the maximum area covered would be 12.3×10^6 ha. This represents 9.1% of all arable land, or an extra 7.3% of the arable land in addition to that receiving sewage sludge in 1990.

Straw incorporation

The same relationship between increase in SOC and straw incorporation was used in this study as presented in Smith *et al.* (1997a,b). As a first approximation, Smith *et al.* 1997a (b) assumed that the baseline level of straw incorporation in Europe was zero. Before the introduction of strict regulations governing straw burning in 1983, this assumption was reasonable, since very little straw incorporation took place (e.g. 2% in UK before 1983; Christian & Ball 1994). However, straw-burning regulations increased the incidence of straw incorporation during the 1980s such that in 1988, 18% of straw in the UK was ploughed-in; MAFF 1989; Christian & Ball 1994). Since figures for the degree of straw incorporation in Europe do not exist, we used the UK 1988 figure for percentage incidence, and applied it to the whole of Europe. From this, we estimated that the area of Europe subject to straw incorporation in 1990 was 18% of cereal land (the part or arable land used to grow cereal crops), which is equivalent to 8.6% of arable land (11.7×10^6 ha).

The application rate of 5.07 t ha^{-1} y^{-1} used by Smith *et al.* (1997a,b) was calculated as the maximum rate possible assuming that all straw was incorporated into the soil on which it was grown. The total amount of straw produced in Europe was estimated from grain yields of cereal crops and typical harvest index values. As Smith *et al.* (1997a) conceded, the incorporation rate used was unlikely to be attainable because of the (unquantified) amount of cereal straw used for other purposes (e.g. animal bedding). In this study, we replace these estimates with estimates of the amount of surplus straw (i.e. after the quantities required for other purposes had been removed) produced in Europe. The quantity of surplus straw produced in the UK has been estimated at between 5 and 7×10^6 t y^{-1} (Stainforth 1982; Prew *et al.* 1995) with the figure of 6.5×10^6 t y^{-1} most commonly used (D.G. Christian, Pers. Comm. 1999; see MAFF 1984). The arable area of the UK represents 4.5% of the arable area of Europe. Assuming the same straw production rate, the UK figure of 6.5×10^6 t y^{-1} was used to estimate the amount of surplus straw produced in Europe. This gave a figure for 1990 European surplus straw production of 145×10^6 t y^{-1}.

Assuming that straw was incorporated evenly across all arable land, the 8.6% arable area assumed to be subject to straw incorporation in the baseline year would receive 12.5×10^6 t y^{-1} of straw. This leaves an annual straw surplus of 132.5×10^6 t y^{-1} to be incorporated in land-management change scenarios. As with animal manure, we used variable incorporation rates for straw (those commonly used for low- to high-yielding cereal crops, MAFF 1984; between 2 and 10 t ha^{-1} y^{-1}) to allow different areas to be used in combined land management scenarios. The statistically significant ($r^2 = 0.41$, $t_8 = 2.38$, $P = 0.04$) relationship between straw incorporation rate and SOC increase of Smith *et al.* (1997a) was used here following:

$$y = 0.1115x + 0.192,$$

where y = % change in SOC y^{-1}, and x = straw incorporated (t ha^{-1} y^{-1})
This gives SOC accumulation rates ranging between 0.42% y^{-1} (for 2 t ha^{-1} y^{-1}) and 1.31% y^{-1} (for 10 t ha^{-1} y^{-1}).

No-till

The same relationship between SOC accumulation rate and no-till (0.73% y^{-1}) as presented in Smith *et al.* (1998a) was used in this study, and, again, changes were applied only to the 0–25 cm layer (with the 25–30 cm layer assumed to be unaffected; see Smith *et al.* 1998a). Apart from increasing SOC accumulation, no-till farming also reduces fossil fuel carbon emissions, even after accounting for the extra herbicides needed (Frye 1984). This fossil fuel carbon saving is estimated to be 23.8 kgC ha^{-1} y^{-1} (Frye 1984; Kern & Johnson 1993). The total carbon mitigation potential of no-till was calculated as the yearly SOC accumulation plus the fossil fuel carbon saving.

No-till/reduced-till agriculture is far less prevalent in Europe than in North America (Lal *et al.* 1998; Smith *et al.* 1998a). The extent of no-till agriculture varies considerably across Europe and, unlike North America (CTIC 1997), accurate figures for the extent of no-till farming are not available (Costa 1997). It is known, however, that even in countries where no-till farming would yield great benefits in terms of water conservation (e.g. Spain), no-till and minimum-till accounted for less than 5% of total arable production as late as 1995 (Costa 1997). In view of these figures, we use an estimate for the percentage of European arable land under no-till agriculture in 1990 of 3% (A. Böhrnsen, Pers. Comm. 1995).

Agricultural extensification

The agricultural extensification scenario reported in Smith *et al.* (1997a,b) relies upon a 20–30% surplus of arable land by 2010 as projected by Flaig & Mohr (1994). Given recent trends in the areas in agricultural set-aside (which has remained relatively constant over the last 10 y), 20–30% surplus now seems very unlikely. A figure of 10% for surplus arable land by 2010 was regarded as more likely and was used here. The implication for the extensification scenario is that less land (1/3 of that in Smith *et al.* 1997a,b) can be taken out of intensive agriculture and put into ley (grass)–arable rotation. Because a 2-in-6 period in grass is required for a viable ley–arable rotation described in Smith *et al.* (1997a,b), the proportion of the rotation in grass cannot be reduced. Instead, the area put into 2-in-6 ley–arable rotation is reduced to one third of that reported in Smith *et al.* (1997a,b).

The same relationship between extensification and change in SOC as reported in Smith *et al.* (1997a) is used, i.e. an SOC accumulation of 1.02% y^{-1} under extensive farming. The area available for extensification of current intensive livestock production is reduced such that the complete extensification of pig and poultry production in Europe (possible with 20–30% surplus arable land; Smith *et al.* 1997a,b) is no longer possible. This scenario uses surplus arable land so any land already under extensive agriculture in 1990 does not enter the baseline calculation. Because extensification takes place on land that was under conventional arable cultivation in 1990, the area under extensive farming on this land in 1990 is, by definition, zero.

Natural woodland regeneration

Smith *et al.* (1997a) cited results from two experiments where changes in SOC were tracked over 100 years of natural woodland regeneration. One of these shows atypically high SOC accumulation. For this reason, the lower estimate of SOC accumulation during natural afforestation (1.17% y^{-1}) was used here. This value for SOC increase is consistent with the recent spatial application of the dynamic SOM models RothC (Falloon *et al.* 1998) and CENTURY (Falloon *et al.* 1999), which showed estimates for the increase in SOC during woodland regeneration reported by Smith *et al.* (1997a) to be too high (Falloon *et al.* 1999).

For above-ground biomass C in trees, we used the mean of the figures of IPCC (1996, p.782; Nabuurs & Mohren 1993) for the average net annual rate of carbon accumulation in broadleaf forests on former agricultural land (range: 2.2–3.4; mean of these figures: 2.8 t ha^{-1} y^{-1}). This replaced the relationship between SOC and above-ground carbon used by Smith *et al.* (1997a,b). Smith *et al.* (1997a) assumed that the wood would be harvested for bioenergy use. In the present paper we developed a separate, dedicated bioenergy production scenario (see below), which assumes that the trees were grown to maturity without harvest.

As for the extensification scenario, the 20–30% surplus of arable land in 2010 projected by Flaig & Mohr (1994) was replaced by a figure of 10%. This scenario uses surplus arable land, so any land already under forestry in 1990 does not enter the baseline calculation. Because natural woodland regeneration takes place on land that was under arable cultivation in 1990, the area under woodland on this land in 1990 is, by definition, zero.

Bioenergy crop production

In this study we assume a similar accumulation of SOC under woody bioenergy crops as that seen under natural woodland regeneration (1.17% y^{-1}; see above). This scenario assesses the carbon mitigation potential of dedicated bioenergy crop production (short rotation woody crops). We assume an annual bioenergy crop production of 12 t ha^{-1} y^{-1} (Hall *et al.* 1981; all production figures are for oven dry tonnes) which is the average production target for 2000 of the EU's Biomass Development Programme (Hall *et al.* 1997). This figure is realistic; average willow (*Salix* spp.) yields in the USA are 13.5 t ha^{-1} y^{-1} with poplar yields even higher under optimal conditions (up to 29 t ha^{-1} y^{-1}; DeBell 1996). In Europe, short rotation woody crops can yield up to 22 t ha^{-1} y^{-1}, even in Mediterranean Europe where yields are lower than in central and Northern Europe (Kofman & Spinelli 1997). The target yield of 12 t ha^{-1} y^{-1} by 2008 is therefore considered attainable (Hall *et al.* 1997).

In the bioenergy production scenario of Smith *et al.* (1997a), a percentage energy utilization of 75% (based on temperate shelter-belts; IPCC 1996, p.755) and an energy substitution factor of 0.75 (the higher figure of Sampson *et al.* 1993) were used. Smith *et al.* (1997b) assumed 50: 50 use of harvested wood for durable bio-products: bioenergy production, and used the same energy utilization and energy substitution factors as Smith *et al.* (1997a). In the present study we assumed that all dry matter was used in bioenergy production. Carbon was assumed to constitute 50% of dry matter. The energy utilization figure of 100% (for dedicated temperate energy crops; IPCC 1996, p.755) was used, as was the mean of the lower (0.65) and higher (0.75) energy substitution factors for dedicated temperate energy crops (i.e. 0.7) of Sampson *et al.* (1993).

As for the extensification scenario, the 20–30% surplus of arable land in 2010 projected by Flaig & Mohr (1994) was replaced by a figure of 10%. This scenario uses surplus arable land so any land already under bioenergy crops in 1990 does not enter the baseline calculation. Because bioenergy crop production takes place on land that was under conventional arable cultivation in 1990, the area producing bioenergy crops on this land in 1990 is, by definition, zero.