Best Practice for Managing Soil Organic Matter in Agriculture

Manual of Methods for ‘Lowland’ Agriculture

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EXECUTIVE SUMMARY

Protecting and enhancing soil organic matter (SOM) levels is a key objective of the Defra draft Soil Strategy for England, and will have beneficial effects for overall soil quality/fertility, carbon storage and erosion control. This report reviews and synthesises recent research on practices for managing SOM in 'lowland' agriculture and identifies best practices for recommendation in England. A partner report (Worrall & Bell, 2009), considers best practices for SOM management in 'upland' agriculture.

Key findings

- Focusing largely on UK studies and reviews, practices that potentially benefit SOM were identified and summarised in a *matrix of management options*, taking into account variations in soil type, agricultural systems and cropping/land-use wherever possible, as well as considering the relative costs, benefits and environmental impacts.

- Two clear 'drivers' were identified for SOM management:
  - *Protection and maintenance* of existing SOM levels for their soil quality and fertility benefits.
  - *Enhancement* of SOM levels for soil carbon storage (to contribute to the mitigation of climate change)

  Management practices (methods) could be broadly divided between these two categories, although some of the methods for the protection and maintenance of existing SOM could also potentially enhance levels.

- Methods that enhance SOM (and carbon storage) were largely associated with *land-use change,* typically taking land out of cultivation thereby reducing SOM oxidation and increasing carbon inputs, viz;
  - Convert tillage land to permanent grassland
  - Establish permanent woodlands
  - Grow biomass crops
  - Introduce rotational grass
  - Water table management (increase the height of the water table)

  It is envisaged that these methods would most likely be incentivised via Environmental Stewardship (as there is an element of 'income forgone' to the farmer).

- Methods that protect and maintain existing SOM levels (and potentially enhance SOM) could be divided into *3 categories*, viz:
  - Reduce soil erosion and hence SOM losses (9 methods)
  - Change tillage practices to reduce SOM oxidation and erosion (adopt reduced or zero tillage systems)
  - Increase organic matter additions via cover cropping, incorporation of crop residues, addition of livestock manures and importing materials high in organic matter (e.g. composts, biosolids, paper crumble, industrial 'wastes' etc.).

  It is envisaged that these methods would most likely be delivered via Cross Compliance measures and incorporated into the requirement to maintain soils in Good Agricultural and Environmental Condition (GAEC).

- A further 6 potential methods for SOM management are cited in the report, but are largely speculative and deemed *insufficiently robust* to promote to farmers/land managers without further investigation and evidence.

- Each method has been described in detail with an assessment of the relative benefit (to SOM and carbon storage), cost, practicality, likely uptake and environmental impact. Both positive (e.g. a reduction in diffuse pollution, increased biodiversity) and negative (e.g. increased risk of soil erosion or gaseous emissions) environmental impacts have been considered, as there were some examples of “pollution swapping”. For example, reduced tillage has the potential to *decrease* erosion and diffuse pollution, but could potentially *increase* nitrous oxide emissions.

- All methods were reviewed and revised (as appropriate) at an Expert Workshop held in London on 17th March 2009, by industry, research and policy representatives.

- A key knowledge gap was the *lack of field measurements* (under UK conditions) of the potential carbon storage/saving benefits of many of the proposed methods, across a range of soil types i.e*. the evidence base to support policy implementation is weak*.

1. INTRODUCTION

1.1. Background

Soil organic matter (SOM) is fundamental to the maintenance of soil fertility and functions, as well as being an important carbon store. However, there is some evidence that soils in the UK may be losing SOM/carbon, probably as a consequence of land-use change; particularly the drainage of peat soils and a legacy of ploughing out grasslands, and this could have implications for climate change (Bellamy *et al.,* 2005; Webb *et al.,* 2001). Protecting and enhancing SOM levels will have beneficial effects for overall soil quality/fertility, carbon storage and erosion control. A key objective of the Draft Defra Soil Strategy (priority area 2) is to "reduce the rate of soil organic matter decline and protect habitats based on organic soils, such as peat bogs, to maintain carbon stores and soil quality" (Defra, 2008). Moreover, the Sustainable Farming and Food Strategy has a target "to halt the decline in soil organic matter in vulnerable agricultural soils by 2025, whilst maintaining as a minimum, the soil organic matter of other agricultural soils, taking into account the impacts of climate change" (Defra, 2002a). In a recent review of the Environmental Stewardship Scheme (Defra & NE, 2008) "providing and protecting carbon storage" was also identified as a key means by which agriculture and land management could contribute to climate change mitigation. Management practices that lead to small increases in SOM storage per hectare of agricultural land could lead to important increases in overall carbon storage at a national level, considering that there are *c.*7.3 million ha of agricultural land in England (comprising *c.*3.4 million hectares of tillage land; *c.*3.3 million hectares of managed grassland; and *c.*0.6 million hectares of rough grazing). This report reviews and synthesises recent research on practices for managing SOM in 'lowland' agriculture (defined as land below the intake wall) and identifies best practices for recommendation in England. A partner report has been prepared by Worrall & Bell (2009), which considers best practice for SOM management in 'upland' agriculture (i.e. peat soils on land above the intake wall).

1.2. Objectives

The overall objective of this work was to review recent research on practices for managing soil organic matter (SOM) in agriculture and identify best practices for recommendation in England

More specifically the objectives of the project were:

- To review recent research on practices for managing SOM in *'lowland'* agriculture and identify which practice, or combination of practices, achieves the greatest benefits for SOM in England.
- To review recent research on practices for managing SOM in *'upland'* agriculture and identify which practice, or combination of practices, achieves the greatest benefits for SOM in England (see Worrall & Bell, 2009).
- To identify any broader environmental or economic benefits/disbenefits of each management practice.
- To consider how the findings can be translated into *advice* for farmers/land managers and incorporated into current Cross Compliance Guidance or incentivised via Environmental Stewardship.
- To hold an *expert workshop* to discuss the findings and identify areas of uncertainty/knowledge gaps for consideration in the final report.

1.3. Methodology

Previous studies for Defra have identified a range of methods for reducing diffuse water pollution, ammonia emissions and greenhouse gas emissions from agriculture (Cuttle *et al*., 2007; Misselbrook *et al*.; 2008, Moorby *et al*., 2007). These have been published as ‘User Manuals’ containing succinct information on the relative effectiveness, cost, practicality and benefit of each of the methods in order to guide policy decisions. To give a consistent approach and enable easy ‘read across’ with these ‘manuals’, recent research on practices for managing SOM in lowland agriculture has been reviewed and summarised in a similar format. Focusing largely on UK studies and reviews (Table 1), practices that potentially benefit SOM were identified and summarised in a matrix of management options, taking into account variations in soil type, agricultural system and cropping/land use wherever possible, as well as considering the relative costs, benefits and environmental impacts. These methods were then reviewed and revised (as appropriate) at an expert workshop held in London on 17th March 2009, by industry, research and policy representatives (see appendix 1 for details).

Management practices (methods) could be broadly divided into those which aim to protect and maintain (and potentially enhance) existing SOM levels for their soil quality and fertility benefits (e.g. reduce soil erosion, change tillage practices and increase organic matter additions) compared with more extreme measures (such as permanent land-use change) with the aim of increasing soil carbon (C) storage (for climate change mitigation); Table 2. It is envisaged that the former would most likely be delivered via Cross Compliance measures, whereas the latter would be more appropriate for incentivisation as part of Environmental Stewardship (where there is a potential loss in income to the farmer). Additional methods are cited in the report, but are largely speculative, based on established theories of SOM turnover (and controlling factors), rather than robust experimental evidence. These were deemed to be insufficiently developed to promote to farmers/land managers without further investigation. It should be noted that within each section methods are given in no particular order.

A brief introduction to each category of methods (land-use change, erosion control, tillage practices, and organic matter additions) describes the mechanism of action and rationale for adopting the methods. Each method has then been given a number and brief title that is used in the tables and for reference. This is followed by a description of the method and its application, arranged into the following sections:

(i) *Description*: a description of the actions to be taken to implement the method.
(ii) *Potential for applying the method*: an assessment of the farming systems, regions, soils and crops to which the method is most applicable.
(iii) *Practicability*: an assessment of how easy the method is to adopt, how it may impact on other farming practices, problems with maximising effectiveness and possible resistance to uptake.
(iv) *Likely uptake*: an assessment of the potential uptake of the method; low, medium or high.
(v) *Costs:* estimates are presented of how much it would cost to implement the method in terms of investment and operational costs, on a per ha basis where available. These were primarily derived from Cuttle *et al.* (2007).
(vi) *Carbon storage effectiveness*: estimates are presented (where available) of the effectiveness of the method in storing carbon (and hence increasing SOM levels). In most cases, estimates were taken from previous Defra projects (e.g. Bhogal *et al.,* 2007; Dawson & Smith, 2006; King *et al.,* 2004); Note: the available data did not provide sufficient information to derive separate estimates for different soil types.

(vii) *Other benefits or risks*: this section provides a largely qualitative assessment of the potential environmental impact of adopting the method. In particular, its impact on diffuse water pollution (nitrate-NO_3, phosphorus-P and faecal indicator organisms-FIOs), gaseous emissions (ammonia-NH_3; nitrous oxide-N_2O and methane-CH_4), soil erosion, biodiversity and energy use (CO_2-C costs/savings).

Using the detailed method descriptions, a summary matrix of the relative benefits/disbenefits of each of the best practice methods was drawn up (Table 3). The relative benefit to SOM (or effectiveness) was broadly quantified using C storage estimates (as detailed above), and compared across soil types (light, medium/heavy or organic/peaty) and land-uses (arable or grass), using expert opinion. Costs (largely from the data in Cuttle *et al.* 2007) were given relative gradings: high, medium or low, none or saving. Similarly, the practicality/likely uptake was graded high (very likely to be taken up), medium or low. Finally, two separate categories were given for environmental impact: positive (e.g. reduction in diffuse pollution, increased biodiversity), or negative (e.g. increased soil erosion or gaseous emissions), as in many cases there were clear examples of “pollution swapping”. For example, reduced tillage has the potential to decrease soil erosion and diffuse pollution (and enhance SOM), but could potentially increase nitrous oxide emissions.

Table 1. Sources of literature on methods to maintain/enhance SOM in 'lowland' agriculture

Report/source	Authors/ Affiliation	Date	Summary
Bioenergy crops and carbon sequestration in soils - a review - NF0418	Cranfield	2001	Reviews current knowledge on the potential for soil carbon sequestration under bioenergy crops and presents data on C sequestration rates for short rotation coppice.
Development of economically & environmentally sustainable methods of C sequestration in agricultural soils - SP0523	ADAS	2003	• Listed management practices that may affect SOM. • Quantified the effect on CO2 and other GHG emissions. • Identified most promising options with respect to cost-effective C sequestration. Detailed assessment of 18 methods. Data on annual C sequestration potential for each method (also spatial distribution).
An Inventory of Methods to Control Diffuse Water Pollution from Agriculture (DWPA) – USER MANUAL (ES0203)	Cuttle *et al*; IGER/ADAS	2007	The User Manual provides succinct information on the cost and effectiveness of various diffuse water pollution control methods. Concentrates on nitrate, phosphorus (P) and faecal indicator organisms (FIOs). 44 methods included.
Benefits and Pollution Swapping: Cross-cutting issues for Catchment Sensitive Farming Policy (WT0706)	IGER/ADAS	2006	Estimates the public benefits from a set of policy options based on the 44 DWPA-User Manual methods (Cuttle *et al*., 2007). These methods were designed to reduce agricultural emissions of nitrate, phosphorus, faecal indicator organisms (FIOs) and sediment.
Vulnerability of organic soils - SP0532	Leeds, Durham, Manchester Universities	2006	Describes potential threats to organic soils in E&W and estimates their likely magnitude, occurrence and impact. A number of management strategies for conserving organic soils were evaluated.
Research into the current and potential climate change mitigation impacts of Environmental Stewardship – BD2302	University of Hertfordshire	2007	Reviews major processes and changes in land use that contribute to GHG emissions in UK agriculture. Applies these processes to changes in land use associated with individual options in each of the three ES Schemes. Recommends preferred ES options to mitigate GHG emissions and suggests other options. Includes data on the potential C sequestration rates of different options
ECOSSE – Estimating Carbon In Organic Soils Sequestration And Emission	Smith et al; Aberdeen University, Macaulay, CEH, NSRI, Rothamsted	2007	The ECOSSE model was developed to predict the impacts of changes in land use and climate change on GHG emissions from organic soils. An objective was to suggest best options for mitigating C and N loss from organic soils.
SP0561 The effects of reduced tillage practices and organic material additions on the carbon content of arable soils	ADAS, Rothamsted	2007	Reviews to what extent reduced tillage practices and organic material returns could increase the C content of arable soils in E&W. Concludes that there is only limited scope for additional soil C storage/accumulation from zero/reduced tillage practices and organic material additions. Questions the implications for N_2O/GHG emissions.
A Review of Research to Identify Best Practice for Reducing Greenhouse Gases from Agriculture and Land Management (AC0206)	Moorby *et al*; IGER/ADAS	2007	Identifies 8 mitigation methods *currently* available as best practice to reduce GHG emissions. Four of the methods apply solely to reducing nitrous oxide (N2O) emissions, two apply to reducing methane (CH4) emissions, and two apply largely to carbon dioxide (CO2) emission mitigation as a result of land use change.

Report/source	Authors/ Affiliation	Date	Summary
Carbon Baseline Survey Project (Natural England FST20-63-025)	Laurence Gould Partnership Ltd, CRED University of East Anglia	2008	This report looked at GHG emissions from typical farm types and used the CALM (Carbon Accounting for Land Managers) tool to estimate these - collecting data from about 200 farms. The report concentrates on estimating typical levels of emissions from the different farm types. Although there is some information on C sequestration rates from the typical farm types (e.g. cereals, dairy, horticulture).
Ammonia Mitigation User Manual	Misselbrook et al; IGER/ADAS/CEH/AEA Technology	2008	Provides information on a range of potential ammonia mitigation methods. 25 methods are described of which 20 are considered to be immediately applicable within the industry, 3 require more development and 2 are speculative.
Environmental Stewardship and Improved Greenhouse Gas Mitigation – Amending Current, and Introducing New Options (BD 2305).	Jarvis and Unwin	2008	Follow on from BD2302. Considered Environmental Stewardship (ES) as a means to implement climate change (CC) mitigation methods. Current ES options were reviewed and new ones suggested. An assessment was made of the potential contribution for CC mitigation and changes recommended to increase their impact. Summary tables of the methods were provided, with comments on the impact on soil C stocks.
User Manual –ALL (WQ0106)	ADAS	Ongoing	Contains a summary of 94 methods to control diffuse water pollution, ammonia and GHG emissions etc. Looks at impacts of the methods on a range of water and air pollutants.
Soils within the Catchment Sensitive Farming Programme: Project to deliver improvements in soil management - SP08014	Rothamsted, GY Associates	Ongoing - accessed Dec 2008	The KEYSOIL website has 30+ case studies showing how farmers have used different OM management strategies (or combinations of methods) to increase profitability. The case studies provide details of the methods used and an estimate of costs and benefits – but no quantification of how much SOM was increased.
Review of carbon loss from soil and its fate in the environment (SP08010)	Dawson & Smith	2006	Provides estimates of total UK terrestrial C stocks and reviews processes and factors influencing C loss and subsequent fate. Includes a section on management options to reduce C loss with some estimates of potential C storage due to land-use change.
The impacts on water quality and resources on reverting arable land to grassland (ES0106)	Williams *et al*.	2008	Measured changes in soil C storage resulting from arable reversion at the Faringdon experimental platform site in Oxfordshire.

2. BEST PRACTICE METHODS

Table 2. Summary of methods which may have beneficial effects on SOM in 'lowland' agricultural systems.

Category	Benefit	Method No.	Method description	Comment
Methods that enhance SOM (and C storage)				
A. Change land use	SOM levels will gradually increase as a result of reduced cultivation (and soil erosion), increased organic C inputs and soil wetness Note: methods 2 & 3 will take land out of food production	1	Convert tillage land to permanent grassland	a) Large scale (whole fields/farms) b) Small scale (e.g. buffer strips, field margins).
		2	Establish permanent woodlands	a) Large scale (whole fields) b) Small scale (e.g. new hedges, shelter belts)
		3	Grow biomass crops	Large scale
		4	Introduce rotational grass	Would need to be established for 2 or more years to provide a benefit.
		5	Water table management	Increase height of water table (at a catchment scale) and /or allow field drainage systems to deteriorate (block drains), to increase soil wetness and reduce SOM oxidation rates
Methods that maintain existing SOM levels				
B. Reduce soil erosion	Reduced SOM losses with particulate material, or as DOC in drainage waters	6	Take action to reduce soil erosion on tillage land and grassland	i. cultivate compacted tillage soil ii. leave autumn seedbeds rough iii. cultivate across the slope iv. manage over-winter tramlines v. early establishment of winter crops vi. fence off rivers and streams from livestock vii. move feed/water troughs at regular intervals viii. loosen compacted soil layers in grassland fields ix. reduce stocking density
Methods that maintain existing SOM levels and potentially enhance C storage				
C. Change tillage practices	Reduction in SOM oxidation and risks of erosion	7	Adopt reduced or zero tillage systems	Reduce the number and/or depth of cultivations.
D. Increase organic matter additions/ returns	Maintain/ enhance SOM levels. Improved soil structure will reduce erosion.	8	Establish cover crops or green manures in the autumn	Will reduce soil erosion and nitrate leaching. Use of deeper rooting species and/or crop residues resistant to decomposition may provide further benefits.
		9	Incorporate straw/crop residues	Increased crop productivity will enhance the amount of residue returned
		10	Encourage use of livestock manures	Increased OC application e.g. by changing to solid manure management, avoiding incineration of poultry litter etc.
		11	Import materials high in OC	Increased OC application e.g. by green and green/food compost, paper crumble, biosolids, mushroom compost, water treatment cake, industrial 'wastes' etc. (biochar)

Speculative methods				
E. Various		12	Convert to organic farming systems	Limited evidence for specific benefit of certified 'organic' systems.
		13	Extensification of outdoor pig and poultry systems onto tillage land	No supporting experimental evidence of a benefit to SOM, although established grassland and animal excreta returns will increase OC inputs. However, soil erosion and diffuse pollution are likely to increase (particularly on sloping land).
		14	Place OM deeper in soil	No supporting experimental evidence. Protects the OM from loss.
		15	Use clover in grassland (mixed sward)	Limited experimental evidence. Relevant to extensive systems and farmers wishing to decrease inorganic fertiliser N use.
		16	Reduce use of lime on grasslands and highly organic soils	Limited experimental evidence. Allowing the pH of organic soils to decrease (e.g. <pH 5.0) can reduce C decomposition rates and DOC solubility. However, sward productivity will decrease, particularly where legumes are an important part of the ecosystem.
		17	Minimise fertiliser (i.e. NPK) use on organic soils	Limited experimental evidence. Fertiliser addition to organic soils can increase SOM decomposition rates ('priming effect').

Table 3. Summary matrix of the relative benefits/disbenefits of best practice methods for managing SOM in 'lowland' agriculture.

	Benefit to SOM (C storage)[1]					Cost	Practicality	Environmental impact[2]	
Land use	Tillage		Grass						
Method / Soil texture	Light	Medium/ heavy	Light	Medium/ heavy	Organic/ peaty			+ ve	- ve
Methods that enhance SOM: A. Land-use change									
1a. Convert tillage land to permanent grassland	***	***	n/a	n/a	***	£££[3]	+	↑↑	~
1b. Buffer strips	***	***	n/a	n/a	***	£	+++	↑	~
2a. Establish permanent woodlands	**	**	*	*	**	~ to +£[4]	+	↑↑	~
2b. Hedges, shelter belts	**	**	*	*	**	£	+++	↑	~
3. Grow biomass crops	**	**	*	*	**	~ to +£	+	↑↑	~
4. Introduce rotational grass	*	*	n/a	n/a	**	~ to £	++	↑	↓
5. Water table management	n/a	n/a	**	**	***	£ to £££	+	↑	↓
Methods that maintain existing SOM: B. Reduce soil erosion									
6. i) Cultivate compacted tillage soil	**	*	n/a	n/a	*	£	+++	↑	~
6. ii) Leave autumn seedbeds rough	**	*	n/a	n/a	*	£	+	↑	↓[5]
6. iii) Cultivate across the slope	**	*	n/a	n/a	*	£	+	↑	~
6. iv) Manage over-winter tramlines	**	*	n/a	n/a	*	£	++	↑	~
6. v) Early establishment of winter crops	**	*	n/a	n/a	*	£	+	↑	~
6. vi) Fence off rivers and streams from livestock	n/a	n/a	**	*	*	££	+	↑	~
6. vii) Move feed/water troughs at regular intervals	n/a	n/a	*	*	*	£	++	↑	~

Method — Soil type	Benefit to SOM (C storage): Sandy/ shallow	Medium/ heavy	Sandy/ shallow	Medium / heavy	Lowland peat	Cost	Practicality	Environmental impact: +ve	-ve
6. viii) Loosen compacted soil layers in grasslands	n/a	n/a	❋❋	❋	❋	£	++	↑	~
6. ix) Reduce stocking density	n/a	n/a	❋	❋	❋	£££	+	↑	~
Methods that maintain existing SOM levels and potentially enhance C storage: C. Change tillage practices & D. Increase organic matter additions									
7. Reduced/zero tillage	❋	❋	n/a	n/a	❋	~ to +£	++	↑	↓
8. Establish cover crops/green manures	❋	❋	n/a	n/a	❋	£	++[6]	↑	~
9. Straw/crop residue incorporation	❋	❋	n/a	n/a	❋	£	+++	~	~
10. Encourage use of livestock manures	❋❋	❋❋	❋	❋	❋	~ to +£	+++	↑[7]	↓
11. Import high OC materials	❋❋	❋❋	❋	❋	❋	~ to +£	+++	↑[7]	↓

Carbon storage effectiveness		Cost	Practicality (likely uptake)	Environmental impact
❋❋❋	Very effective	£££ high	+++ high	↑↑ Highly beneficial (impact over large area); ↑ medium/low benefit
❋❋	Moderately effective	££ medium	++ medium	↓ risk of "pollution swapping"
❋	Some effect	£ low	+ low	~ neutral (no benefit or risk)
n/a	Not applicable	~neutral		
		+£ saving		

[1] The relative benefit to SOM was broadly quantified using C storage estimates where available (see individual method sheets for details).
[2] Environmental impact separated into positive (e.g. reduction in diffuse pollution, increased biodiversity), or negative (e.g. increased soil erosion or gaseous emissions), as in many cases there were clear examples of "pollution swapping". See individual method sheets for details.
[3] Cost estimates assume conversion to extensive grassland
[4] Cost high in establishment phase, but potential for long-term income from selling wood products
[5] Possible increased need for herbicides and slug damage.
[6] Not practical on many medium/heavy soils
[7] The *overall* environmental benefit will only be positive under 'best practice' management.

3. METHOD DETAILS

3.1. CATEGORY A: LAND-USE CHANGE

Rationale/mechanism of action: Permanent cropping can increase SOM (& C) storage due to the avoidance of annual cultivations which stimulate the mineralisation of organic matter leading to carbon losses as CO_2. Changing from arable agriculture to *permanent* cropping (grassland & biomass production) is therefore expected to markedly reduce C losses and enhance SOM levels. Similarly, the creation of farm woodlands can enhance SOM levels (by reducing losses via mineralisation) and increase C storage (in both soils and vegetation). Converting areas of land on a farm to grass buffer strips, hedges/shelter belts etc will have a similar effect, albeit on a smaller scale. Likewise, avoiding the ploughing out of grasslands to tillage land will markedly reduce C losses. Indeed the extensification of grassland (i.e. from improved grassland with periodic ploughing and reseeding, to semi-improved or unimproved grassland with no ploughing and reseeding) has been suggested to increase SOM levels.

In a comprehensive review of C loss from soil and its fate in the environment, Dawson and Smith (2006) provided estimates of the potential gains/losses of soil C for a range of land-use changes under temperate conditions, using data from studies undertaken largely in Europe, USA, Australia and New Zealand. The conversion of grassland or permanent cropping to tillage cropping was estimated to result in C losses in the range 2.2 to 6.2 tCO_2e/ha/year. These losses were largely due to vegetation clearance, increased soil organic matter decomposition rates upon cultivation and losses of C through erosion (Freibauer *et al.,* 2004). For example, Figure 1 clearly demonstrates soil OC loss as a result of ploughing out grassland for tillage cropping at two sites on silty soils in Lincolnshire (Garwood *et al.,* 1998). Here, the decline in soil C (0-15 cm) was equivalent to 33 t C/ha and 13 t C/ha (i.e. 3.8 and 1.5 tCO_2e/ha/year), respectively.

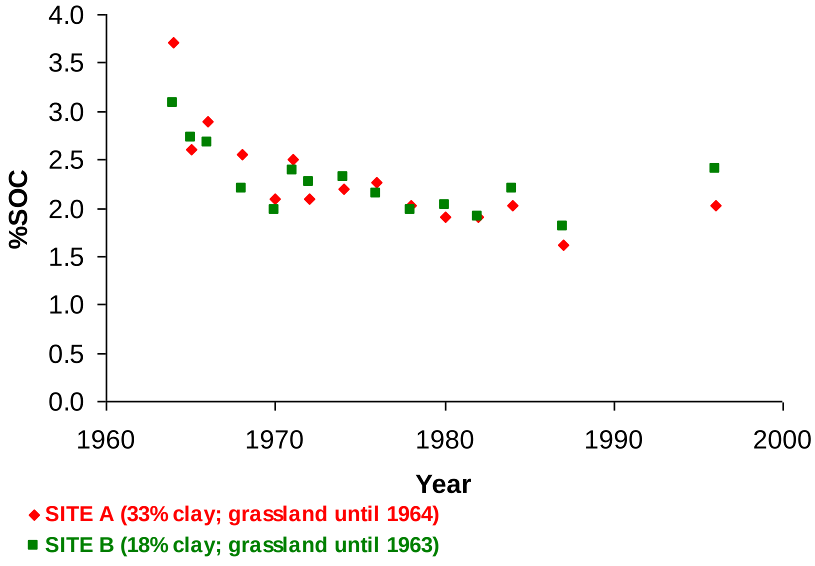

Figure 1. Decline in topsoil (0-15cm) organic carbon (SOC) following the ploughing-out of long-term grassland in Lincolnshire, UK (Garwood *et al.,* 1998).

In contrast, the conversion of tillage land to grassland can result in increased C storage in the range 1.1 to 7.0 tCO_2e/ha/year (Dawson & Smith, 2006). Indeed, recent results from a medium-term arable reversion experiment on a heavy clay soil (54% clay) at Faringdon in Oxfordshire (Figure 2; Williams *et al*., 2008) showed a 24% increase in soil C (0-15 cm) after 6 years of arable reversion to grassland (equivalent to 9.2 tCO_2e/ha/year). Conversion of tillage land/grassland to forestry has been estimated to increase soil C storage in the range 0.4 to 2.3 tCO_2e/ha/year (Dawson & Smith, 2006). However, there will also be C stored in the vegetation itself, which Dawson and Smith (2006) estimated to range between 0.3 and 5.6 tCO_2e/ha/year depending on the tree species, harvest frequency and climatic conditions.

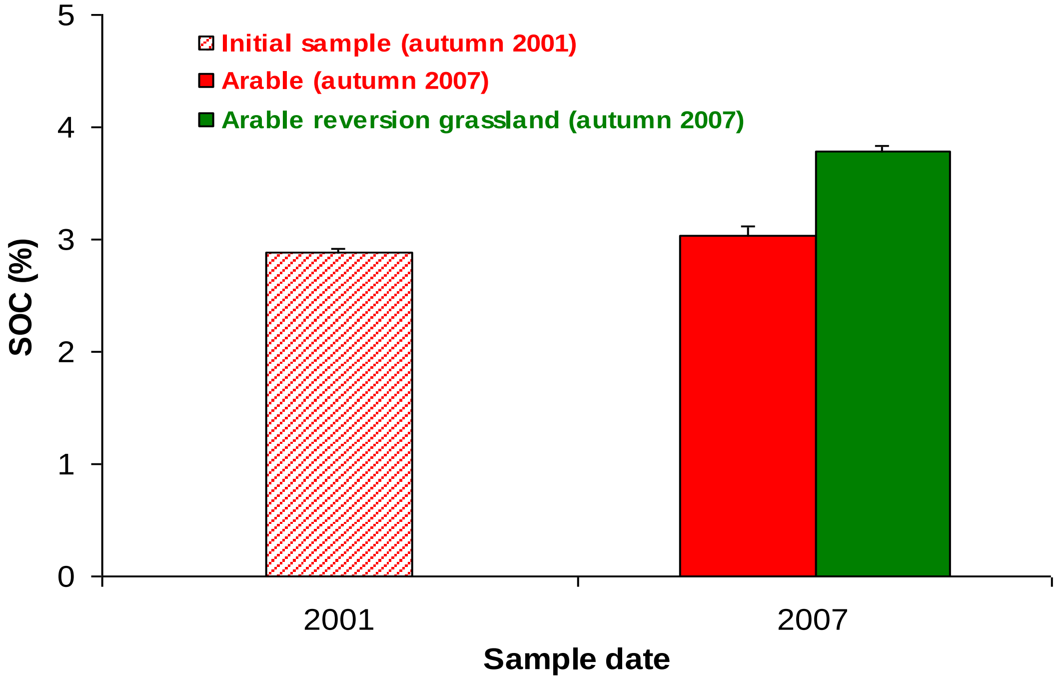

Figure 2. Changes in soil organic carbon (SOC) on arable reversion grassland plots at Faringdon (Oxfordshire) between 2001 and 2007.

The quantity of C that can be stored in any soil is finite. After a change in management practice, SOM (& C) levels increase (or decrease) towards an equilibrium value (after *c.*100 years or more) that is characteristic of the soil type, land use and climate (Johnston & Poulton, 2005). The relatively 'high' annual rate of SOM accumulation (C storage) in the early years after a change in land-use cannot be maintained indefinitely and the annual rate of SOM increase will decline (eventually to zero) as a new equilibrium is reached. It is therefore unlikely that the initial rate of increase in SOM following a change in land-use/management practice will be sustained over the longer term (>50 years), as a new equilibrium level is reached. Carbon storage is also reversible. Maintaining a soil at an increased SOM level, due to a change in management practice, is dependent on continuing that practice indefinitely. Indeed, SOM is lost more rapidly than it accumulates (Freibauer *et al.,* 2004). Only if land is taken *permanently* out of cultivation (i.e. to permanent grassland or woodland), will the benefits of SOM accumulation and C storage be realised over the long-term. This obviously has implications for rotational cropping, although the introduction of rotational grass or grass/clover leys has been shown to increase SOM by *c*.1%/yr (Smith *et al*., 1997) due to a reduction in the frequency of tillage (equivalent to a saving 1.76 tCO_2e/ha/yr; King *et al.,* 2004), although the evidence for this is limited.

Method 1a. Convert tillage land to permanent grassland

Description: Increase SOM by changing the land use from tillage land to either ungrazed or grazed permanent grassland.

Potential for applying the method: The method is applicable to all forms of tillage land, but whole-scale conversion is potentially most suited to marginal tillage land that was historically kept as grazing land (e.g. steeply sloping land, shallow soils). Benefits will be greatest on soils low in organic matter.

Practicability: Large scale conversion of tillage land to permanent grassland is an extreme change in land use that is unlikely to be adopted by farmers, without the provision of suitable financial incentives. It may be particularly suited to areas where the converted land would have amenity or conservation value.

Likely uptake: Uptake of large-scale conversion is likely to be low due to the drastic impact on farm practice, requiring a complete change in farm business outlook.

Costs:

Total cost		£/ha
Ungrazed	Capital	0
	Annual	95
Grazed	Capital	890
	Annual	195

There is no capital cost where the land is un-grazed. However there are significant costs annually due to the loss of income from the arable crops, plus the cost of cutting.
In a grazed system there is a very significant initial capital outlay, due to the cost of purchasing livestock. The annual costs are also greater, however, profit from the livestock would largely offset this (Cuttle *et al*., 2007)

Carbon storage effectiveness: Where land use change is to permanent grassland, increased soil C storage is likely to initially (estimated to occur for up to 20 years) be in the range 1.9 to 7.0 tCO_2e/ha/year (Dawson & Smith, 2006). The actual value will depend on soil type, previous land use and climate, as well as the land area undergoing conversion, and rates will slow and eventually cease when a new equilibrium of soil C is reached (estimated to be after 50-100 years).

Other benefits or risks:

- The method is very effective in reducing nitrate (NO_3) leaching. Conversion to ungrazed grassland has been estimated to reduce NO_3 losses by >95% (Cuttle *et al*., 2007). If the converted land is used for extensive grazing (e.g. beef/sheep farming) NO_3 leaching losses are likely to be reduced by >50% (Cuttle *et al.,* 2007).
- Emissions of nitrous oxide (N_2O) would be reduced according to the area of land taken out of annual cultivation. Direct N_2O emissions are likely to be reduced as a result of lower inorganic fertiliser N additions (depending on previous inorganic fertiliser N addition levels) and indirect N_2O emissions as a result of lower nitrate leaching losses. However, indirect N_2O emissions would increase from grazed grassland as a result of emissions from livestock manure management.
- Conversion to grazed grassland would result in increased ammonia (NH_3) emissions, as a result of livestock and manure management.

- Conversion has been estimated to result in a *c.*50% reduction in the loss of P in the absence of grazing and a *c*.42% reduction under extensive grazing (Cuttle *et al.,* 2007).
- Conversion to ungrazed grassland would have no effect on faecal indicator organisms (FIOs), but extensive grazing would increase losses at the farm-scale because of the livestock providing a source of viable FIOs (Cuttle *et al.,* 2007).
- If the land was grazed (compared to previous tillage cropping), methane (CH_4) emissions would increase at the farm level, due to grazing ruminant livestock. However, this would only increase national CH_4 emissions if they were additional stock.
- There is much potential for a change in biodiversity value with changes in land use, although such improvements are not certain (e.g. Cole *et al*., 2007). A detailed analysis of this aspect of change in land use is beyond the scope of this study.
- There would be reductions in energy use on the farm and hence indirect CO_2-C savings.
- ***Taking land permanently out of production will result in a loss of farm income and reduces the land area for food production***.

Method 1b. Establishment of permanent field or riparian buffer strips

Description: Increase SOM by the establishment of permanent in-field or riparian grass buffer strips (as in Entry Level Stewardship-ELS; or Higher Level Stewardship-HLS), as well as permanent set-aside.

Potential for applying the method: The method is applicable to all forms of tillage farmland. Benefits will be greatest on soils low in organic matter.

Practicability: The establishment of permanent buffer strips is often more achievable than large scale conversion to permanent grassland.

Likely uptake: Uptake is likely to be dependent on the financial rewards offered by incentive schemes.

Costs: There is no capital cost. However, there will be some loss of income from the reduced area available for arable cropping.

Total cost		£/ha
Capital		0
Annual	In-field	32
	Riparian	16

(Cuttle *et al*., 2007)

Carbon storage effectiveness: See Method 1a - overall C storage will be lower because of the smaller land areas involved. However, in-field and riparian buffer strips would have an added advantage of reducing soil C losses through soil erosion from adjacent sloping tillage land (see Method 6).

Other benefits or risks:

- See Method 1a.

Method 2a. Establish permanent woodlands

Description: Increase SOM by changing the land use from tillage or grassland to permanent woodland.

Potential for applying the method: The method is applicable to all forms of tillage land and grassland, but large-scale conversion is potentially most suited to marginal tillage land that was historically kept as grazing land.

Practicability: Large-scale woodland creation is an extreme change in land use that is unlikely to be adopted by farmers, without the provision of suitable financial incentives. It may be particularly suited to areas where the converted land would have amenity or conservation value. Grants are currently available to establish new woodlands (e.g. the Forestry Commission's English Woodland Grant Scheme).

Likely uptake: Uptake of large-scale woodland creation is likely to be low due to the drastic impact on farm practice, requiring a complete change in farm business outlook.
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Cost: There is a potential saving of £150/ha of tillage land or grassland due to reduced inputs and cultivation (D. Harris ADAS, pers. comm.). However, there would be a significant cost annually due to the loss of income from the farming system (although the sale of wood products could offset this over the long-term).

Carbon storage effectiveness: Reported estimates of soil C storage from the conversion of tillage land to forestry are variable. For example, Dawson & Smith (2006) estimated an initial (20 years) increase in soil C storage in the range 1.1 to 2.3 tCO_2e/ha/year (50% uncertainty) for tillage land conversion, with a lower estimate for grassland conversions (0.4 tCO_2e/ha/year; 95% uncertainty). Estimates from Defra project BD2302 suggested a C storage rate of 3.0 tCO_2e/ha/year for tillage land and 3.4 tCO_2e/ha/year for grassland, whereas King *et al.* (2004) suggested an increase of 2-3 tCO_2e/ha/year for arable land and no change for grassland. In practice, C storage will depend on soil type, previous land use and climate, as well as the land area undergoing conversion, and rates will slow and eventually cease when a new equilibrium of soil carbon is reached (estimated to be after 50-100 years).

Other benefits or risks:

- The method is very effective in reducing NO_3 leaching. Woodland creation has been estimated to reduce NO_3 losses by >95% (Cuttle *et al.,* 2007).
- A reduction in direct N_2O emissions through lower inorganic N fertiliser inputs would be expected, according to the area of land taken out of annual cultivation, and depending on the previous inorganic fertiliser N addition levels. Indirect N_2O emissions would decrease as a result of lower nitrate leaching losses.
- In the longer term, there may be green house gas (GHG) substitution benefits through the increased use of timber products.
- Long-term biomass stocks (and associated C storage) would be increased with woodlands, with C storage in the biomass estimated in the range 0.3 and 5.6 tCO_2e/ha/year depending on the tree species, harvest frequency and climatic conditions (Dawson & Smith, 2006), although higher values have been reported (e.g. Defra, 2007).

- Creation of farm woodland has been estimated to reduce the loss of P by 50% in the absence of cultivation, with similar sediment loss reductions in surface runoff expected.
- A reduction in FIO losses would be expected through a change from grazed land to woodland, otherwise no change would be expected.
- There is much potential for a change in biodiversity value with changes in land use, although such improvements are not certain (e.g. Cole *et al.,* 2007). A detailed analysis of this aspect of change in land use is beyond the scope of this study.
- There would be reductions in energy use on the farm and hence indirect CO_2-C savings.
- ***Taking land permanently out of production will result in a loss of farm income and reduces the land area for food production.***

Method 2b. Establish farm woodlands/hedges

Description: Increase SOM by the small-scale creation of farm woodland/hedges, as described in various ES options (e.g. new hedges, shelter belts, in field trees and field corner management options).

Potential for applying the method: The method is applicable to all forms of tillage farmland and grassland.

Practicability: The establishment of small 'pockets' of woodland, new hedges and in-field trees may be more achievable than large scale schemes.

Likely uptake: Uptake is likely to be dependent on the financial rewards offered by incentive schemes.

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Cost: There will be some loss of income from the reduced area available for tillage cropping or grass production.

Carbon storage effectiveness: See Method 2a - overall C storage will be lower because of the smaller land areas involved. However, establishing new hedges would have an added advantage of reducing soil C losses through soil erosion from any adjacent sloping tillage land (see Method 6).

Other benefits or risks:

- See Method 2a

Method 3. Grow biomass crops (i.e. willow, poplar, miscanthus)

Description: Increase SOM by growing perennial biomass crops (e.g. willow, poplar, miscanthus) to displace fossil fuel use, either through direct combustion or through biofuel generation (e.g. by gasification).

Potential for applying the method: The method is applicable to all forms of tillage farmland. There would be little or no benefit to SOM levels through converting grassland to biomass crops.

Practicality: A change in land use to biomass cropping is unlikely to be adopted by farmers, without the provision of suitable financial incentives. Defra's Energy Crop Scheme closed to new applications for establishment grants in June 2006.

Likely uptake: Low, due to changes to the farming system, unless financial remuneration is available.

Cost: Neutral up to potential savings of £10/ha of tillage land (D. Harris, ADAS, pers. comm.)

Carbon storage effectiveness: Estimates of the potential C storage from biomass cropping are largely based on those for woodland creation where poplar or willow are grown, and from arable reversion to grassland where miscanthus or other energy grasses are grown. Conversion of tillage land to *permanent* willow or poplar cropping has been estimated to *initially* (10 years) increase soil C storage in the range 2.0-3.0 tCO_2e/ha/year, depending on soil type, previous land use and climate (King *et al*., 2004). For miscanthus and other energy grasses, estimates were slightly lower at 1.8-2.7 tCO_2e/ha/year. Dawson and Smith (2006) estimated a value of 2.4 tCO_2e/ha/year for conversion to bioenergy production. As with woodland creation, there will also be significant C storage in the biomass itself. However, it should be noted that most biomass crops have a life-span of *c.*25 years (20 years for switch grass and 5 years for reed canary grass) before re-establishment.

Other benefits or risks:

- This method will be effective in reducing NO_3 leaching because the land is not cultivated annually and inorganic fertiliser N rates are low-moderate.
- Direct emissions of N_2O would be reduced due to reductions in inorganic fertiliser N addition rates and indirect emissions due to the absence of annual cultivation and associated lower NO_3 losses.
- It has been estimated that permanent biomass cropping would result in an overall 50% reduction in the loss of P (in the absence of cultivation), with similar sediment loss reductions in surface runoff expected.
- The effects of biomass crops such as short-rotation coppice willow and miscanthus on biodiversity and wildlife value have been encouraging (e.g. Sage *et al.,* 2006), although not entirely clear; and are being investigated further in Defra project IF0104.
- Biomass crops have a greater demand for water than most tillage crops.
- A change of land use from food (human and livestock) crops to biomass crops has implications for the sustainability of food production in the UK. Increased use of prime land for energy crop production would lead to greater reliance on food imports. Also, increased production of cereals in other countries to supply UK needs

may lead to greater deforestation of land to grow crops and use of practices (overseas) that result in a net increase of GHG emissions, in addition to increase fuel use for food transport.

Method 4. Introduce rotational grass

Description: Increase SOM by introducing rotational grass or grass/clover leys for 2 years (or more) in a 6 year rotation (often termed agricultural extensification), thereby reducing the frequency of tillage operations.

Potential for applying the method: The method is applicable to all forms of tillage farmland.

Practicality: A change in land use to rotational cropping is unlikely to be adopted by farmers without the provision of suitable financial incentives.

Likely uptake: Low, due to the changes to the farming system, unless financial remuneration is available.

Cost: Would depend on farm specific circumstances i.e. the proportion of cover and longevity of the grass ley, plus any livestock produce from the grassland area.

Carbon storage effectiveness: The benefits to soil C storage of introducing ley-arable cropping are questionable, with conflicting evidence. In particular, there is uncertainty about how much of the potential increase in SOM from a 2 year ley will be maintained over the long-term. Results from the long-term ley-arable experiments at Rothamsted and Woburn, demonstrate that the inclusion of 1-3 years grass leys within an arable rotation, have very little effect on SOM (Johnston & Poulton, 2005), with a 1 year ley having no effect on SOM levels, and a 3 year ley increasing SOM by 13-28% (measured after 15-28 years), compared to annual tillage cropping. Using these results, together with results from two European studies, Smith *et al.,* (1997) estimated a potential C storage rate of 1.02%/yr compared to annual tillage cropping, equivalent to 1.76 tCO_2e/ha/yr (King *et al.,* 2004).

Other benefits or risks:

- Increased risk of NO_3 leaching on ploughing out the grass leys. However, this is likely to be balanced (or indeed outweighed) by N ‘immobilisation’ in accumulated SOM reserves.
- Direct emissions of N_2O could be reduced during the ley phase of the rotation due to reductions in inorganic fertiliser N addition rates (dependent on the management of the ley).
- A reduction in P losses is likely during the ley phase, due to the permanent grass crop cover.
- There would be reductions in energy use through the lack of annual cultivations and hence indirect CO_2-C savings.
- Depending on use of the ley phase of the rotation there could be a reduction in potential food and fibre production (and hence farm incomes).

Method 5. Water table management

Description: Increase the height of the water table (at a catchment scale) and/or allow existing (old) drainage systems to naturally deteriorate, i.e. cease to maintain them (or block them). This will increase soil wetness and reduce SOM oxidation rates.

Potential for applying the method: This method is most applicable to grassland soils. It is also highly relevant to lowland organic/peaty soils, such as the Fens, where peat shrinkage and subsidence following drainage has led to considerable SOM losses (Holden *et al.,* 2007). The rewetting of Fenland soils has therefore been proposed as a measure for peat conservation. However, rewetting will inevitably limit the current use of this land for high output arable production and most likely result in arable reversion to grassland. There are around 6 million hectares of drained soils in England and Wales. Drainage deterioration is compatible with the HLS Scheme hence farmers may be able to obtain payment by, for example, restoring traditional water meadows. However, this method is not applicable to tillage land, as without an effective drainage system, economically sustainable arable cropping would not be possible on many heavy soils, particularly for farmers growing potatoes and sugar beet in the east of the country.

Practicability: The method is easy to implement, with the natural deterioration of drains requiring no necessary action. However, at the catchment scale an integrated Water Management Plan would need to be developed and approved by stake holders.

Likely uptake: Low, with considerable resistance from farmers to adopting this method as a deliberately managed activity, without any financial incentive. Although, the natural deterioration of many field drainage systems is probably occurring in practice, because farmers do not have the funds to replace ageing systems.

Cost: There will be a substantial loss of income due to reduced production levels.

Carbon storage effectiveness: There have been a limited amount of studies on the effects of raising the water table on soil C storage in lowland agricultural systems. Evidence from drainage studies largely conducted on upland peat soils have shown that soil respiration would decrease, but methane production would increase (see upland report by Worrall & Bell, 2009). Rewetting Dutch peat grasslands reduced the production of CO_2 from the soil by 14% (Best and Jacobs, 1997).

Other benefits or risks:

- Drainage systems can accelerate the delivery of agricultural pollutants from land to a watercourse, by acting as a preferential (by-pass) flow route. Allowing drainage systems to deteriorate therefore reduces hydrological connectivity and the potential transfer of pollutants to the watercourse. Also, water is forced to percolate through the soil at a slower rate, thereby increasing the opportunity for the retention or transformation of potential agricultural pollutants through physical filtration and biological activity in the soil. However, on sloping land there is a potential for surface run-off losses to increase. This method was assessed in balance to reduce both nitrate leaching and P losses (Cuttle *et al.,* 2007).
- If soils are wetter for longer, it is likely that nitrous oxide emissions will increase, though the size of any increase will depend mainly on inorganic fertiliser addition rate changes from previous management.

- There is a risk of increased poaching and surface run-off if drains are allowed to deteriorate (but overall losses of P, sediment and FIOs are likely to be smaller than from drained systems).
- The risk of pollutant transfer in surface run-off is particularly high where organic manures and inorganic fertilisers are applied to waterlogged soils on sloping ground.
- Undrained grassland will wet up earlier in autumn so that stock need to be removed earlier to avoid poaching. Overall stocking rates will also need to be reduced.
- Methane production is likely to increase for example, Best & Jacobs (1997) measured reduced CO_2 production by rewetting peat grasslands, but methane production increased 3-fold.

3.2. CATEGORY B: REDUCE SOIL EROSION

Rationale/mechanism of action: Soil erosion by water or wind can result in a significant loss of SOM associated with the eroding soil particles from agricultural fields, as well as in dissolved forms (DOC). In the Woburn Erosion Reference Experiment (Bedfordshire), loss of C by erosion accounted for 2-50% of soil C change (Quinton *et al*., 2006). For England and Wales, estimates of the amount of C-mobilized by erosion processes range between 200 and 760 ktC/yr, of which 80-290 ktC/yr is re-deposited and 120-460 ktC/yr is transported to surface waters (Quinton *et al*., 2006). Whenever soil particles are detached and carried by surface flow, silt and clay particles and organic matter are carried farthest – often to streams and rivers far away from the field of origin (Anon., 2005a). According to the Defra 2007 Farm Practice Survey, at least one incidence of soil erosion happens on 12% of holdings every year and on a quarter of holdings at least every 3 years (Anon., 2007). Soil erosion of some description has been observed on over 50% of farms.

Lighter soils, such as those with a high sand or silt content, tend to be more prone to erosion than those with stronger structures. In a study across England, mean annual soil erosion data varied between 0.22 t/ha/yr (medium and light loams, Cumbria) to 4.89 t/ha/yr (medium silts and loams, Somerset), (Brazier *et al*., 2001). However, the factors that control soil erosion and deposition are complex, and although inherent soil properties play a role in determining the level of erosion, slope angles and forms, weather and cropping management all affect loss rates.

There are two types of erosion by water; sheet erosion (from flows over the soil surface) and channel (rill and gully) erosion, with the latter tending to occur where soils lack vegetative cover (Dawson and Smith, 2006). However, on many farmland hill slopes, erosion rates from cultivation operations are similar to erosion rates caused by water (Govers *et al*., 1999). Surface run-off usually occurs during heavy storms or following prolonged rainfall, but can be accelerated if soil infiltration rates are reduced. Wind erosion can also cause a substantial loss of SOM in exposed landscapes (Smith *et al*., 2001). In England, this mainly affects agricultural land in the Midlands, East Anglia and Yorkshire (Dawson and Smith, 2006). Wind speed timing, soil dryness and surface roughness, texture and land use are important determinants of wind erosion potential

Maintaining good soil structure and promoting water infiltration and through-flow, reduces soil erosion risks and subsequent loss of SOM. In addition, good soil structure also promotes the efficient use of soil nutrients. Woodlands and the establishment of permanent pasture or cover crops (methods 1, 2 & 8) reduce erosion as the vegetation cover helps to protect the soil from the erosive impact of rainfall. In addition, minimal tillage cultivation systems (method 7) reduce soil disturbance and retain crop residues on the soil surface, thus reducing the risk of soil erosion. For bare soil or where there is little residue or vegetation to intercept rainfall, surface run-off risks will be increased. However, an increase in surface roughness through appropriate cultivations will encourage infiltration, as well as help reduce the erosive energy of any surface flow that is generated. Where land is sloping, furrows, tramlines and tracks orientated down the slope will tend to collect water and develop concentrated surface flow paths. This risk will be reduced if they are aligned across the slope (where slopes are even), increasing down-slope surface roughness and reducing the risk of developing surface sheet and rill flow.

Vegetated in-field buffer strips located along the contour on upper slopes or in valley bottoms function as sediment traps, and reduce the transfer of diffuse pollutants in surface run-off from agricultural land to water. Likewise hedges act as ‘natural’ buffer strips and sediment traps and help to protect soils from wind erosion. According to the 2008 Defra Farm Practice Survey, the most common actions taken to reduce run-off, water and wind erosion in the last 12 months were working across rather than down slopes, loosening of tramlines and fencing watercourses to prevent stock eroding banks (Anon., 2008).

Appropriate land management can thus, help to reduce the risks of surface run-off and erosion, and maintain or enhance SOM.

Method 6. Take action to reduce soil erosion on tillage and grassland

A large (i.e. whole field) or small-scale (e.g. buffer strips or new hedges) change in land use, for example from tillage land to permanent grassland (including the establishment of field margins and buffer strips, methods 1 a&b) or the establishment of farm woodlands/hedges/shelter belts (methods 2 a&b) will reduce soil erosion. Other methods that reduce soil erosion, include the establishment of cover crops (method 8) and reduced/zero tillage systems (method 7). These methodologies are described in more detail in the relevant section of this document. The following section outlines a number of additional methods to reduce soil erosion and retain SOM in both tillage and grassland systems.

i. Cultivate compacted tillage soil

Description: Reduce soil erosion through the cultivation of compacted tillage soil, with discs or tines during dry conditions, well ahead of the start of drainage in late autumn. When soils are compacted or capped and there is little crop residue or vegetation to intercept rainfall, land can be susceptible to the generation of surface run-off and the movement of pollutants to a water body. Cultivation can disrupt soil surface compaction/crusts and increase surface roughness, enhancing water infiltration and drainage through the soil profile, rather than creating surface run-off. To further reduce erosion, a vegetative cover could be established over-winter either from natural regeneration or from broadcast grain etc.

Potential for applying the method: The method is applicable to tillage land where soils are compacted, particularly in high winter rainfall areas.

Practicality: The cultivation itself is straightforward. However, for the method to be effective it should be carried out in the late summer to early autumn (i.e. when soils are dry), when there can be many other competing demands for the farmer’s time.

Likely uptake: Where compaction is identified as an issue uptake is likely to be high due to the simplicity of the method.

Cost: Light surface cultivation of tillage land to reduce soil erosion risks costs *c*.£4/ha/yr (Cuttle *et al.,* 2007).

Carbon storage effectiveness: Reductions in soil/sediment losses by cultivating compacted tillage soils have been estimated at 25% for a clay loam soil and 35% for a sandy loam soil (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique. However, this may partly be offset by increased oxidation losses following tillage (see category 3).

Other benefits or risks:

- Cultivation of compacted tillage soils in the autumn will enhance the mineralisation of soil organic N and water infiltration rates into the topsoil. This will increase the risk of NO_3 leaching by a small extent over the winter.
- A reduction in the soil component of phosphorus loss by an estimated 25% for a clay loam soil and a 35% reduction for a sandy loam soil (Cuttle *et al*., 2007).

ii. Leave autumn seedbeds rough

Description: Reduce soil erosion through the avoidance of operations that create a fine seedbed that will 'slump' and run together. A more open seedbed is achieved by using a reduced number of cultivations, particularly from powered cultivation equipment, and by avoiding the use of a heavy roller. This helps to reduce the risk of surface run-off by reducing soil capping and enhancing infiltration of surface water into the soil. A rough seedbed also helps to break up any surface flow that is generated, reducing the risk of sheet wash and rill/gully development.

Potential for applying the method: Applicable to the establishment of autumn-sown crops on tillage land. It is most applicable to winter cereal crops that can establish well in coarse seedbeds.

Practicality: The method is best suited to those crops that are able to establish effectively in a rough seedbed. As a result, it is not well suited to crops such as oilseed rape and reseeded grassland that require fine, clod-free seedbeds. Herbicide activity is most effective in firm and fine seedbeds; a rough seedbed can reduce activity. Also rough seedbeds can exacerbate slug problems.

Likely uptake: Low, due to the associated weed/pest control problems.

Cost: The cost may be zero (or even a saving on cultivation costs), but could be up to *c.*£100/ha if yield losses and increased costs from slug and weed control occurred; an average of £40/ha has been estimated (Cuttle *et al*., 2007).

Carbon storage effectiveness: Reductions in soil losses by leaving autumn seedbeds rough have been estimated at 25% for a clay loam soil and 35% for a sandy loam soil on sloping land (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique.

Other benefits or risks:

- 'Patchy' crop establishment or indeed crop failure due to a rough seedbed would reduce yields and lead to an increased risk of NO_3 leaching over the winter following harvest, as well as the risks associated with sediment losses from bare soils over winter following drilling.
- Enhanced infiltration rates may increase NO_3 leaching losses to a small extent as the water passes through the soil profile rather than over the surface as run-off.
- Herbicide activity is most effective in firm and fine seedbeds. A rough seedbed could reduce activity
- A rough seedbed may not be appropriate when there is a high risk of slug damage.
- A reduction in P losses of 35% and 25% for sandy loam and clay loam soils, respectively, has been estimated (Cuttle *et al*., 2007).

iii. Cultivate across the slope

Description: Furrows and tramlines orientated down the slope will tend to collect water and develop concentrated surface flow paths. Soil erosion can be reduced through cultivating and drilling across the slope. This reduces the risk of developing sheet and rill flow as the ridges created across the slope increase down-slope surface roughness and provides a barrier to surface run-off. Soils cultivated across the slope will also hold more water in surface depressions.

Potential for applying the method: Applicable to all tillage soils on sloping land, where slopes are regular.

Practicality: The method is more time-consuming and requires greater skill than conventional field operations. Cultivation and drilling should not be carried out across very steep slopes, due to the risk of machinery overturning. Consequently, this method is only likely to be effective for crops grown on gently sloping fields, with simple slope patterns. For steeper sloping fields with complex slope patterns, it is not practical to follow the contours accurately. In these fields, attempts at cultivations across the slope often lead to channelling of run-off water, particularly in tramlines or wheelings, which can cause severe gully erosion. For furrow crops, such as potatoes and sugar beet, harvesters only work effectively up and down the slope and therefore limit the practicality of this method being used.

Likely uptake: Low, as a result of only being practicable to cultivate across the slope on gently sloping fields with simple patterns; however, in localised areas it can be a useful technique.

Cost: The additional time required will depend on the size and configuration of the field. The cost of this method has been estimated at £3/ha (Cuttle *et al*., 2007). However, if more sophisticated techniques, such as a hillside combine, were needed, the cost could be higher.

Carbon storage effectiveness: Reductions in soil losses by cultivating across the slope have been estimated at 25% for a clay loam soil and 35% for a sandy loam soil (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique.

Other costs and benefits:

- Depending on soil type a reduction in P losses of between 25% (clay loam) and 35% (sandy loam) have been estimated, accompanied by a corresponding reduction in sediment loss (Cuttle *et al*., 2007).
- The method has no effect on nitrate leaching losses.

iv. Manage over-winter tramlines

Description: The management of over-winter tramlines can help to prevent soil erosion, as tramlines can act as flow pathways increasing surface run-off. Therefore, avoiding their use in winter can reduce run-off volumes and prevent the down-slope transport of sediment-bound and soluble pollutants. If tramlines are required (e.g. for the application of pesticides), then tines can be used to disrupt the tramlines and increase surface roughness to encourage water infiltration, or they can be superimposed on the drilled crop.

Potential for applying the method: This method (either avoiding or disrupting/drilling tramlines) is applicable to winter cereals in all arable farming systems, particularly on light soils in areas with high winter rainfall. Tramline management (rather than avoidance) could also be potentially useful method to reduce soil erosion for a range of winter cropping.

Practicability: The avoidance of tramlines will only be possible where winter access to land, e.g. for pesticide application, is not required. However, in these situations tramline disruption or drilling are simple methods that can reduce the incidence of soil erosion.

Likely uptake: Where winter access is not required the uptake is likely to be medium.

Cost: If the spraying out of tramlines in spring was required there would be a need to mark out and make adjustments to the sprayer to treat only selected rows. This would be more time consuming and costly than conventional spraying. The cost of this has been estimated at £4.50/ha (Cuttle *et al.,* 2007).

Carbon storage effectiveness: Reductions in soil losses by tramline management have been estimated at 25% for a clay loam soil and 35% for a sandy loam soil (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique.

Other costs and benefits:

- Depending on soil type a reduction in P loss of between 25% (clay loam) and 35% (sandy loam) has been estimated, accompanied by a corresponding reduction in sediment loss (Cuttle *et al*., 2007).
- The method has no effect on nitrate leaching losses.

v. Early establishment of winter crops

Description: Harvest crops such as maize and sugar beet early (e.g. September rather than October), and establish autumn sown crops early (ideally by mid September). Earlier harvesting of crops, especially those that are traditionally harvested late, will mean that harvesting is likely to be undertaken when soil conditions are drier, avoiding severe compaction and soil damage that can generate surface run-off. Also, the early establishment of autumn sown crops means the crop will be in the ground earlier, and will result in more established vegetation cover to protect the soil from the erosive impacts of rainfall.

Potential for applying the method: The method is applicable to all tillage systems growing late harvested crops, especially in high rainfall areas.

Practicality: The early harvesting of crops such as maize and sugar beet can 'clash' with the harvesting of winter cereals, creating more work at a time when farmers are already very busy.

Likely uptake: Medium, there can be yield penalties from early harvesting and there may be a 'clash' with other farm operations.

Cost: No added harvesting/cultivation costs – but there may be a yield penalty in some situations.

Carbon storage effectiveness: This is has not been quantified as there are no experimental data available on the potential reduction in soil erosion by adopting this method, however, similar reductions to those delivered by method 8 can be expected.

Other costs and benefits:

- This method is likely to reduce nitrate leaching due to a reduction in the time soils are left fallow in the autumn, as well as soil P losses, due to a reduction in soil erosion.

vi. Fence off rivers and streams from livestock

Description: Reduces soil erosion of river/stream banks by the construction of stock-proof fences in grazing fields and on tracks adjoining rivers and streams. Livestock, particularly cattle, can cause severe trampling damage to river/stream banks when attempting to gain access to drinking water. The vegetative cover is destroyed and the soil badly poached, leading to erosion of the bank and increased transport of soil particles and associated P into the watercourse. Fencing to prevent access to the banks eliminates this source of erosion and SOM loss, as well as associated waterway pollution (particularly from FIOs).

Potential for applying the method: The method is applicable to farms with grazing livestock and to all soil types. Benefits will be greatest on heavily stocked farms, particularly those with cattle. The method is not applicable to outdoor pigs, as these are more securely fenced and do not have access to rivers or streams.

Practicality: The method would be less feasible on upland beef/sheep farms with extensive areas of rough grazing and considerable lengths of unfenced river/stream banks. There would also be a need to provide an alternative source of drinking water.

Likely uptake: This method is only likely to be adopted where stream bank erosion is severe and an alternative water source can be provided.

Costs: There will be an initial capital investment in fencing required (*c.*£3/m), as well as maintenance costs and a requirement for an alternative water source in many cases. For a dairy farm with twelve fields adjacent to water Cuttle *et al.* (2007) estimated annual costs of £11/ha (including amortised capital costs).

Carbon storage effectiveness: The method has been estimated to reduce soil losses by 50% from the area at risk to stream bank erosion (Cuttle *et al*., 2007). However, this will only be a small proportion of the total farm area, even for farms with large river/stream bank areas.

Other benefits or risks:

- Livestock can add nutrients and FIOs directly by urinating and defecating into the water. Preventing access eliminates this source of pollution (Cuttle *et al*., 2007).
- The method has been estimated to reduce the soil and manure components of P losses by 50% (Cuttle *et al*., 2007).
- The method will also reduce water pollution risks from ammonium-N, suspended sediment and enhanced levels of biological oxygen demand (BOD).

vii. Move feed/water troughs at regular intervals

Description: Feeding troughs, feeding racks and water troughs for outdoor stock should be re-positioned at regular intervals to reduce damage to the soil and improve the distribution of excreta. Troughs and racks should be moved more frequently when the soil is wet and easily poached. They should not be sited close to water courses.

Potential for applying the method: The method is more applicable to beef/sheep systems than dairy, where feed is commonly provided in the field (except for buffer feeds). It is especially relevant to farms where livestock are out-wintered. Indeed, feed troughs and feeding points are already routinely moved on some farms. There is a greater risk of poaching from cattle than from sheep, with outdoor pigs particularly destructive. The potential to reduce poaching will be greatest on imperfectly and poorly drained soils.

Practicability: The regular re-positioning of feeding troughs/racks is a simple method, with few limitations to its implementation. However, it is more difficult to vary the position of water troughs. This would probably require use of a bowser or installation of a number of permanent drinking points within the field, as used on dairy farms that employ a strip-grazing system. However, this can be a considerable cost to the business. This method may not be applicable to land that is very easily poached, where frequent moving of feeding points may increase the number of poached areas and make the situation worse. So, the method would only really be effective when applied in combination with method 6ix) to reduce field stocking rates when soils are wet. In some situations, it may be necessary to locate the feeding point on a hard-standing. In all cases, feeders and troughs should be located away from water courses to break the hydrological link between the poached area and surface water.

Likely uptake: Medium, depending on the location of water sources

Cost: Low cost (<£10/ha, D. Harris, pers. comm.), for moving feed troughs/racks, but more expensive if water troughs need to be moved.

Carbon storage effectiveness: The method has been estimated to reduce soil losses by 15% (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique.

Other benefits or risks:

- This method will have minimal effect on nitrate leaching losses.
- Introduction of this method has been estimated to reduce soil P losses by 15% and losses by 10% (Cuttle *et al.,* 2007).
- The method would also reduce water pollution from ammonium-N, sediment and enhanced levels of BOD.
- There may also be reductions in gaseous losses of ammonia, nitrous oxide and methane.

viii. Loosen compacted soil layers in grassland fields

Description: Reduce soil erosion and loss of organic matter from grassland fields by shallow spiking or topsoil loosening to disrupt compacted soil layers in dry/moist conditions. Trampling by livestock, particularly cattle, and the passage of heavy farm machinery can compact the upper layers of grassland soils in both grazing and silage fields. As the soil is cultivated only infrequently, the compaction can persist and build-up over a number of years. As a result, porosity is reduced and this impedes the percolation of rainwater and slurry, increasing the risk of surface run-off. Shallow spiking or topsoiling can break up the compacted layer and allow more rapid infiltration of water, thus reducing run-off from the soil surface. In addition, soil aeration can be improved and roots are able to penetrate deeper into the soil, which will increase water and nutrient uptake from deeper soil layers.

Potential for applying the method: The method is applicable to all grassland farms, but particularly those with high cattle stocking rates.

Practicality: There are few limitations to the adoption of this method although loosening operations may be more difficult on stony soils. Also, the timing of the loosening operation is important so as not to damage the grass sward or to cause smearing of the soil.

Likely uptake: Where compaction is identified as an issue, uptake is likely to be high due to the simplicity of the method.

Cost: For a typical dairy farm, the costs of topsoil loosening (using a flat-lift) have been estimated at £43/ha (Cuttle *et al*., 2007).

Carbon storage effectiveness: The method has been estimated to reduce the soil component of P loss by 70% and 50% for sandy loam and clay loam soil types, respectively (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique. However, this may partly be offset by increased oxidation losses following cultivation (see category 3).

Other costs and benefits:

- A reduction in the soil component of P loss by 70 and 50% for sandy loam and clay loam soil types, respectively (Cuttle *et al*., 2007).
- Reduced surface run-off will also decrease water pollution by nutrients etc., particularly following manure/inorganic fertiliser applications.
- Where slurry has been applied, increased infiltration will reduce gaseous ammonia emissions.
- Improved infiltration and aeration of the soil will reduce nitrous oxide emissions but may slightly increase nitrate leaching losses.

ix. Reduce stocking density

Description: Poaching can exacerbate the transport of sediment (and nutrients) to watercourses by exposing bare soil and increasing surface run-off. A reduction in stocking density can help to minimise soil structural damage from poaching and hence reduce soil/sediment losses.

Potential for applying the method: The method is applicable to all livestock farms, but will have the greatest impact on heavily stocked units where the risks of soil structural damage are greatest. Poaching is generally more severe with cattle grazing than with sheep, and is particularly severe with outdoor pigs.

Practicality: The method is relatively simple to put into practice, but the main factor limiting its adoption would be the reduction in farm income resulting from reduced stock numbers. It is most likely that a reduction in livestock would be achieved through a reduction in the number of livestock farms, rather than by reducing the numbers of stock on individual farms. A moderate reduction in the overall stocking rate can be achieved on dairy farms by reducing the cow replacement rate, so that fewer young stock need to be kept on the farm. Some dairy farms may convert to extensive beef/sheep systems. Reducing stock numbers might encourage farms to become more reliant on clover-based swards to reduce costs by replacing inorganic N fertiliser with biologically fixed N.

Likely uptake: Very low, due to the impact on overall farm profitability. In most cases farmers' would require additional funding incentives to reduce stocking rates.

Costs: Cuttle *et al*. (2007) estimated the cost of a 50% reduction in livestock numbers on individual farms to result in a halving of the gross margin on dairy, beef and outdoor pig farms.

Annual cost for farm systems	**Dairy**	**Beef**	**Outdoor pigs**
Cost £/ha	309	55	2,700
With additional change to a clover-based system using no inorganic fertiliser N			
Cost £/ha	274	35	n/a

Source: Cuttle *et al*., (2007)

Carbon storage effectiveness: The method has been estimated to reduce the soil component of P loss by 18% for a sandy loam soil (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique.

Other benefits or risks:

- Reducing the number of stock will reduce the amounts of excreta and manure produced per unit area. In particular, much of the NO_3 leached from grazed pastures originates from urine patches. With lower stocking rates, there would be fewer urine patches and less NO_3 available for leaching.
- A 50% reduction in livestock numbers has been estimated to reduce N leaching by 10-25 kg N/ha on a dairy farm; and 3-5 kg N/ha on a beef/sheep farm (Cuttle *et al*., 2007).
- Reducing stock numbers (by 50%) has been estimated to result in a reduction in soil, manure and inorganic fertiliser P losses from dairy or beef farms of up to 35% on clay loam soils (Cuttle *et al*., 2007).

- As the farm would need to produce less forage, inorganic fertiliser rates would also be reduced.
- There will also be reductions in NH_3, CH_4 and N_2O losses, as well as FIOs (Cuttle *et al*., 2007).

3.3. CATEGORY C: CHANGE TILLAGE/CULTIVATION PRACTICES

Rationale/mechanism of action: Most commonly, tillage crops are established in the UK by mouldboard ploughing to a depth of at least 20 cm (typically 20-25 cm), followed by secondary cultivations (e.g. harrow, powered tillage, disc/tine) to provide a seedbed for drilling ('conventional tillage'). Cultivations are carried out in the autumn for all winter-sown and some spring-sown crops. Reduced tillage is a term that is used to describe all non-plough based cultivation practices. At the extreme, zero tillage ('no-till') is where seed is drilled directly into an uncultivated soil surface ('direct drilling') or simply broadcast onto the soil surface. Most commonly in reduced tillage systems, crops are established using shallow cultivation techniques (i.e. discs or tines) working to 10-15 cm (or less), or even just following rotary-harrowing of the soil surface (i.e. combined harrow and drill techniques). In England and Wales in 2005, *c*.50% of primary tillage practices used mouldboard ploughing ('conventional tillage') and *c.*43% used reduced tillage methods (i.e. heavy discs, tines or powered cultivators), with direct drilling/broadcasting (i.e. no cultivation) occurring on *c.*7% of the tillage area (Anon., 2005). Provisional figures for 2006 suggest a similar distribution (Anon., 2006a). The main drawbacks to zero tillage in the UK have been grass weed and disease problems, and the build-up of soil compaction.

Reduced tillage has been widely promoted as a potential means of increasing SOM levels and storing C within soils, due to less soil disturbance (and hence SOM decomposition) and reduced soil erosion rates. The effects of tillage practices on SOM levels have largely been derived from medium-long term experiments measuring changes in soil C following the adoption of a particular tillage practice. Bhogal *et al.* (2007) critically reviewed the extent to which reduced tillage practices could increase the C content of arable soils in the context of England and Wales. Most studies reported in the literature have been carried out in North America and Australia (e.g. Alvarez, 2005; Follett, 2001; VandenBygart *et al*., 2003; West & Post, 2002,) where the benefits of reduced tillage are recognised (in terms of water conservation) and zero-tillage is widely carried out. Although even here, many of the increases in SOM measured following reduced/zero tillage were confined to the top 10-15 cm. Where deeper soil samples have been taken, apparent differences between tillage systems have often disappeared (Baker *et al.,* 2007; Machado *et al.* 2003).

There have only been a limited number (6 studies) of contrasting tillage studies in the UK (Cannell and Finney, 1973; Powlson and Jenkinson, 1981; Chaney, 1985; Ball, 1994). Taking an average of the soil C changes measured in these studies, Bhogal *et al.* (2007) estimated an initial C storage potential of 1.14 tCO_2e/ha/yr for zero tillage under UK conditions (up to c.20 years). This equates to c.0.35% of the typical organic C content of an arable soil in England and Wales (@ 91 t/ha, assuming 28 g/kg C in the topsoil; Webb *et al.,* 2001). Reduced tillage was estimated to have half the C storage potential of zero tillage at 0.59 tCO_2e/ha/yr. These estimates of potential C storage increases from zero and reduced tillage should NOT be considered to be annually cumulative, as typically tillage land in the UK is ploughed every 3 to 4 years to reduce the build-up of weeds, diseases and soil compaction levels. It is arguable that much (if not most) of the stored C will subsequently be released as a result of the soil disturbance caused by ploughing.

There is also limited evidence that zero/reduced tillage can increase direct emissions of nitrous oxide (N_2O) by up to an equivalent of *c*.0.70 tCO_2e/ha/year (compared with conventional tillage), due to an increase in topsoil wetness and/or reduced aeration as a result of less soil disturbance (MacKenzie *et al.,* 1998; Goulding *et al*., 2007). Nitrous oxide is a powerful greenhouse gas with 310 times the global warming potential of CO_2, such that overall, increased N_2O emissions may completely offset the balance of greenhouse gas emissions compared with the amount of C potentially stored through changing from conventional to reduced/zero tillage practices. However, the evidence is not clear and further work is required to determine the effect of contrasting tillage systems on N_2O emissions, C storage and the overall balance of greenhouse gas emissions.

Any tillage practice that reduces the level of soil disturbance is likely to have an impact on SOM levels, due to a potential reduction in SOM decomposition rates and losses. Therefore, the avoidance of root crops and associated deep cultivations could potentially help maintain SOM levels in vulnerable soils.

Method 7. Adopt reduced or zero tillage systems

Description: Reduce SOM decomposition rates, by using discs or tines as a primary cultivation (rather than ploughing) in seedbed preparation (reduced till); or direct drill into stubbles (zero-till).

Potential for applying the method: This method is already adopted on a number of arable farms, with around 1.5 million hectares cultivated using discs or tines in England and Wales. It is most commonly applied to medium to heavy soils, although the practice is increasingly being carried out on lighter soils.

Practicability: No-till is generally unsuitable for light soils, largely because of compaction build-up risks. Reduced tillage is less appropriate in a wet autumn and only where any lower topsoil/subsoil structural problems have been alleviated. Reduced tillage may increase resistant weed populations and therefore increase reliance on chemical control (Davies *et al.,* 2006). Commonly reduced tillage land is ploughed every 3-4 years to relieve compaction problems and to control grass weeds/diseases.

Likely uptake: Aside from the issues raised above, the expense of purchasing new equipment is the largest barrier to uptake, as such it is only likely to be used on larger predominately combinable crop farms.

Cost: Implementation is likely to result in a net saving due to reduced labour and tractor time (Cuttle *et al.,* 2007).

Annual **savings**	Arable
Likely net **savings** £/ha	40

Carbon storage effectiveness: Crop establishment using zero tillage has been estimated to have an initial C storage potential of 1.14 tCO_2e/ha/yr under UK conditions (95% confidence interval: -0.5, 2.79). Reduced tillage has been estimated to have half the C storage potential of zero tillage at 0.59 tCO_2e/ha/yr (Bhogal *et al.,* 2007; Chambers *et al*., 2008). These estimates can only be regarded as the initial rate of increase (up to <20 years), and will slow and eventually cease when a new equilibrium soil C level is reached. They should also not be considered to be annually cumulative, as arable land in the UK is typically ploughed every 3 to 4 years to reduce the build-up in weeds, diseases and soil compaction levels. It is arguable that much (if not most) of the stored C from reduced/zero tillage practices will subsequently be released as a result of the increased soil disturbance caused by periodic ploughing.

Other benefits or risks:

- There are many benefits of adopting reduced/zero tillage cultivation systems besides the possibility of increasing soil C levels. Reduced tillage is effective at protecting and therefore maintaining existing SOM from decomposition, leading to improvements in soil structure, infiltration and water retention. Reduced tillage also protects soils against soil water/wind erosion, with reductions in surface run-off particularly effective when a mulch of crop residues is left on the surface.
- Reduced soil erosion will lead to a decrease in P and sediment losses. In the short-term, total P losses in surface run-off have been estimated to decrease by 5% from clay loam soils (Cuttle *et al.,* 2007). However, in the long-term following repeated reduced tillage research has shown that dissolved P losses can increase.

- Nitrate leaching will decrease to a small extent (0-5 kg N/ha) compared with ploughing, through reduced mineralisation of SOM following autumn cultivation (Cuttle *et al*., 2007).
- There is a possibility in some circumstances that the incorporation of large volumes of straw into a small volume of soil under a reduced tillage system may immobilise so much N that it will restrict crop growth and create a need for autumn application of inorganic fertiliser N. Note: recommended inorganic fertiliser N application rates are currently the same on ploughed and reduced/zero tilled land (Anon., 2000).
- There will be reduced production costs and fossil fuel savings due to a reduction in cultivation energy inputs. These have been estimated to be 0.08 tCO_2e/ha/year from reduced/zero tillage compared with ploughing (Bhogal *et al.,* 2007).
- There is limited evidence that zero/reduced tillage can increase direct emissions of N_2O by up to an equivalent of *c*.0.70 tCO_2e/ha/year (compared with conventional tillage), due to an increase in topsoil wetness and/or reduced aeration as a result of less soil disturbance (MacKenzie *et al.,* 1998; Goulding *et al.,* 2007). In contrast, reduced tillage systems have been estimated to decrease indirect N_2O emissions by up to *c.*0.03 tCO_2e/ha/year, due to decreased nitrate leaching losses (0-5 kg/ha) following autumn cultivation (Cuttle *et al*., 2007). Nitrous oxide is a powerful greenhouse gas with 310 times the global warming potential of CO_2, such that overall, increased N_2O emissions may completely offset the balance of greenhouse gas emissions compared with the amount of C potentially stored through changing from conventional to reduced/zero tillage practices.

3.4. CATEGORY D: INCREASE ORGANIC MATTER ADDITIONS/RETURNS

Rationale/mechanism of action: A steady decline in livestock numbers over recent years in the UK coupled with high output of livestock production, has led to a decrease in the amounts of livestock manure applied to land (Jenkinson, 1988; FAO, 2005). In addition, advances in harvest efficiency have meant more effective removal of agricultural crops with consequently fewer crop residues left on the field, and the breeding of shorter straw length cereals has led to lower straw residue returns. Changes to grassland management practices, such as the increased production of silage rather than hay (Poulton, 1996), have also reduced the quantity of organic matter returned to soil. Furthermore, improvements in farm machinery (such as combine harvesters and silage cutters) have also led to increased crop residue removal (Dawson and Smith, 2006).

Topsoil organic matter increases can be directly related to organic matter inputs (Dick & Gregorich, 2004), with increases measured following both the application of organic manures and inorganic fertilisers, the latter due to increased crop residue returns (Schjonning *et al.,* 1994; Christensen & Johnston, 1997; Nicholson *et al.,* 1997). The recycling of organic materials to land is generally considered to be the best practicable environmental option for utilising the properties of these materials. Currently, around 90 million tonnes of farm manures (Williams *et al.,* 2000), 3-4 million tonnes of biosolids (Gendebien *et al.,* 1999; Chambers, 1998) and 4 million tonnes of industrial 'wastes' (Gendebien *et al.,* 2001) are applied (on a fresh weight basis) annually to agricultural land in the UK. These materials provide a valuable source of both nutrients and organic matter that could potentially increase SOM levels (Table 4). In addition to these organic materials, crop residues (particularly cereal straw), provide a means of returning C to soils, with an estimated 15 million tonnes of C potentially returned to UK arable soils (5 million ha) in straw, stubble and chaff each year (Bhogal *et al.,* 2007). Cover crops/green manures also have the potential to increase SOM, by protecting the soil from erosion over winter, and adding C following soil incorporation. The C:N ratio is an important determinant of residue quality and can influence initial nutrient turnover rates from applied sources (Dawson and Smith, 2006). The use of deeper rooting species and decomposition resistant crop residue species (high C:N ratio) may provide further benefits.

Table 4. Typical organic carbon additions from selected organic materials applied at a rate of 250 kg/ha total N (Anon., 2000; Chambers, 1998; Gendebien *et al*., 1999, 2000; Gibbs *et al.,* 2005)

Manure type	Application rate (t or m^3/ha FW)	Dry matter (%)	Organic C (t/ha)
Cattle FYM	42	25	4
Dairy slurry	83	6	2
Broiler litter	8	60	2
Digested sludge cake	33	25	3
Green waste compost	36	65	5
Paper crumble	75[a]	40	9

[a]Typical application rate of primary or secondary chemical/physically treated paper crumble = 75 t/ha fresh weight (equivalent to 150 kg/ha total N), Gibbs *et al.* (2005).

Method 8. Autumn establishment of cover crops or green manures

Description: Increase SOM through the establishment of cover crops on land that would otherwise be bare over-winter, an effective cover crop may be established immediately post-harvest or, at the latest, by mid-September. An alternative is to under-sow spring crops with a cover crop that will be in place to take up nutrients and provide vegetation cover once the spring crop has been harvested. In order to protect the soil surface throughout the period when runoff could occur, the cover crop should be destroyed close to the land being prepared for the following crop.

Potential for applying the method: This method is particularly applicable on light soils (and especially sloping land) where there are significant areas of spring crops. The cover crop can be established cheaply through seed broadcast followed by a light tine cultivation and rolling. The method can also be used in some grassland systems by under-sowing maize and spring barley, with a grass seed mixture.
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Practicality: It is difficult to establish a cover crop that will develop sufficient biomass to benefit SOM levels and reduce NO_3 leaching losses, ahead of sowing most autumn crops. For under-sown spring crops, some farmers prefer to wait until the main crop is established before under-sowing. However, this may only be practicable on well-drained soils. A cover crop can also be broadcast into the main crop before harvest, however, this may damage the standing crop and lead to some yield losses. Except where grass is being established as the following crop, autumn or post-harvest establishment of mustard (or a similar crop) is likely to provide the most effective cover.

Likely uptake: Depends on the crop rotation and soil type. Where cover cropping is possible, a medium uptake is expected. However, overall uptake is expected to be low because of soil type and cropping limitations.

Costs: In most combinable crop fields, there will be good ground cover of volunteer plants and weeds following harvest if left uncultivated. In this case, the root balls of the harvested crop plants will hold the soil together well and a light spring tine harrowing may be all that is necessary to assist re-growth and ground cover at a cost of £10/ha/year. In other crops, ground cover may be poor due to the lack of re-growth and the time of year of the harvest operation. Cultivation costs would then be incurred for cover crop establishment at *c*.£17.50/ha plus an average cost of £50/ha for the seed, giving a total of £67.50/ha (Cuttle *et al*., 2007).

Carbon storage effectiveness: Cover cropping has been shown to result in short-term (less than one season) increases in SOM (Sainju *et al.* 2000; 2001; 2002). Additionally, the annual use of cover cropping has been shown to maintain SOM levels, where SOM had otherwise decreased. For example, Sainju *et al.* (2002) measured a 25% decrease in SOM following six years of conventional tillage without cover crops, whereas with a hairy vetch cover crop (returning *c.*0.7 tC/ha/yr) SOM levels only declined by 1 % and with a rye cover crop (returning *c.*3.7 tC/ha/yr) SOM levels increased by 3-4 %. In the UK, cover crops such as mustard, rye, volunteer wheat/barley/oats have been shown to be an effective management tool for reducing over-winter nitrate leaching losses (Cook & Froment, 1996). No measurements of potential C storage increases have been made, but with typically only 0.5-1.0 t/ha above-ground biomass production (Harrison & Peel, 1996), soil incorporation is likely to have limited benefit to SOM levels. Indeed, the main benefit of cover cropping is likely be due to a reduction in soil erosion and associated loss of soil C on sloping land, rather than organic matter addition via crop incorporation, as the green material tends to rapidly decompose. The method has been estimated to reduce the soil component of P loss by 25% on a sandy loam soil and 35% on a clay loam (Cuttle *et al*., 2007). It can be assumed that similar reductions in SOM losses would be expected by adoption of this technique.

Other benefits or risks:

- Depending on growth of the cover crop and the time of onset of drainage, typical nitrate leaching loss reductions have been estimated in the range 10 to 45 kgN/ha in the year of establishment (Cuttle *et al*., 2007).
- Cover cropping has been estimated to reduce the soil component of P losses by 25% and 35% on clay loam and sandy loam soils, respectively (Cuttle *et al*., 2007).
- Soil structural damage caused by establishing a cover crop late in wet conditions may compromise cover crop establishment. Residual NO_3 will be at risk of leaching from soils with a poorly established cover crop and soil structural damage will increase the risk of soil erosion and the loss of P and sediment.

Method 9. Incorporation of straw/crop residues

Description: Increase organic matter additions through the incorporation of straw or crop residues directly into the soil after harvest.

Potential for applying the method: Crop residues, particularly cereal straw, provide a means of returning organic C to soils, with an estimated 15 million tonnes of C returned to UK arable soils (5 million ha) in straw, stubble and chaff each year (Bhogal *et al*., 2007). The incorporation of straw and crop residues is widely practised in UK agricultural systems, where straw burning in the field is no longer permitted. Improved harvest efficiency in recent years has tended to minimise the amount of straw and crop residue remaining for incorporation after harvest. Additionally, plant breeding has reduced cereal straw lengths.

Practicality: The practicality of this method is high and it is already common practice on a wide range of farming systems.

Likely uptake: Uptake is already high and it is debatable whether it is practical to increase straw residue incorporation on a large-scale given the competing demands for straw as animal bedding, field vegetable mulches, as an energy source etc.

Cost: There will be a small cost for straw chopping on a combine and cultivation into the soil (*c*.£10/ha).

Carbon storage effectiveness: The incorporation of cereal straw has the potential to increase SOM of agricultural soils in England and Wales by 50 kg C/ha/yr/t straw applied (with 95% CI in the range 20-80 kg C/ha/yr/t), based on measurements at 8 study sites in England (Bhogal *et al.,* 2007). At typical incorporation rates (7.5 t/ha fresh weight), this equates to an increase of 0.37 t C/ha/yr (1.36 tCO_2e/ha/yr), which represents *c.*0.41% of the typical carbon content of an arable topsoil in England and Wales (assuming 28 g/kg soil organic C, 1.3 g/cm^3 bulk density and 25 cm soil depth; Webb *et al.,* 2001). However, this can only be regarded as the initial rate of SOM increase (up to *c.*20 years), as SOM accumulation rates decline with time.

Other benefits or risks:

- Incorporating crop residues that do not contain much nitrogen, such as cereal straw, into the soil in autumn will lead to small (<5kgN/ha) reductions in the amount of nitrate leached. In comparison with straw/crop residue removal, straw incorporation will cause some additional retention of N in SOM. This may cause short-term immobilisation of N, which in some circumstances may lead to the need for additional inorganic N fertiliser.

Method 10. Encourage use of livestock manure

Description: Increase organic matter additions through the regular application of livestock manures.

Potential for applying the method: The method can be applied to all types of cropping system where livestock manure is available or could be brought-in. It is particularly relevant to arable systems where it has been suggested (e.g. King *et al.,* 2004; Smith *et al.,* 1997) that manure should be preferentially targeted (rather than grassland), because arable soils tend to have lower SOM contents and hence a greater potential for increased SOM storage, although there are no robust scientific data to support this view. However, as most farm manures (the exception being *c*.580,000 tonnes of poultry litter that are used for electricity generation) are currently applied to land and livestock numbers are decreasing, sourcing additional supplies of livestock manure may be difficult for arable farms, particularly in areas where livestock farming is scarce.

There are several Codes of Practice and pieces of legislation that seek to 'control' the application of farm manures to agricultural land e.g. The Water Code (MAFF, 1998), Nitrate Vulnerable Zones (NVZs) Action Programme (Defra, 2002b) and recently introduced Cross Compliance measures and associated Statutory Management Requirements. In particular in NVZs, the application of organic materials should not exceed the field rate limit of 250 kg/ha total N per annum, and the overall farm N loading rate on arable land of 170 kg/ha total N.

Practicality: The addition of livestock manure to land is common practice on stocked farming systems and within many arable systems. However, there may be practical limitations to the uptake of this system on stockless systems related to manure availability and sourcing. Where the farmland is in a Nitrate Vulnerable Zone (NVZ), the application of manures must comply with the NVZ Action Programme rules (2009) on application rate limits (no more than 250 kg/ha total N may be spread as handled manure) and 'closed period' timings for high readily available N manures (i.e. slurries and poultry manures) on all soil types.

Likely uptake: High, although uptake will depend both on the availability of livestock manure for land application, as well as the price of inorganic fertiliser alternatives and the logistics of handling manures.

Cost: The use of livestock manures is likely to be at least cost neutral or most probably will result in a saving (due to the saving in inorganic fertiliser use).

Carbon storage effectiveness: The application of livestock manures to agricultural soils in England has the potential to increase SOM by an average of 60 kg C/ha/yr per tonne of manure dry solids applied, with 95% confidence intervals in the range 16-102 kgC/ha/yr/t (Bhogal *et al*., 2007). At a typical application rate equivalent to 250 kg/ha total N, *c*.0.63 t/ha/year (2.3 t CO_2e/ha/yr) additional carbon could be retained in the topsoil. This equates to 0.7% of the typical C content of an arable soil in England and Wales (*c*.91 t/ha, assuming 28 g/kg soil organic C, 1.3 g/cm^3 bulk density and 25 cm soil depth; Webb *et al.,* 2001). However, this can only be regarded as the initial rate of SOM increase (i.e. up to *c*.20 years), as SOM accumulation rates will decline over time. Dawson and Smith (2006) estimated that the incorporation of either solid manure or slurry could sequester between 0.73-5.5 t/ha CO_2e/ha/yr.

Other benefits or risks:

- Livestock manures provide a valuable source of plant available nutrients, particularly nitrogen (N), phosphorus (P), potassium (K), sulphur (S) and magnesium (Mg), thereby reducing the need for inorganic fertiliser inputs and usually result in considerable financial savings to the farmer.
- A reduction in inorganic fertiliser usage will result in energy consumption savings involved in manufacturing inorganic fertilisers (particularly N), with estimates in the range 0.2-0.3 tCO_2e/ha from a typical livestock manure application (Bhogal *et al.,* 2007).
- The application of livestock manures also presents a risk of environmental pollution, *if not handled and managed carefully*. Applications therefore need to be managed to limit N losses by NH_3 volatilisation and N_2O emission to air, and $NO_{3,}$ P and FIO losses to water.
- Nitrate leaching losses can occur following autumn/winter manure applications, depending on factors such as application timing, speed of incorporation and rainfall after application. Cuttle *et al.* (2007) suggest that there could be an increase in nitrate leaching of 1-10 kg N/ha from regular additions of livestock manure. Leaching risks are greatest from high readily available N manures (e.g. slurries and poultry manures) when applied to nitrate leaky sandy and shallow soils.
- Significant soil P enrichment can occur where manures are applied annually, which can in the long-term lead to increased P losses, principally via soil erosion. Also, in the short-term, incidental P losses can occur in surface runoff and drainflow soon after manure application.
- Ammonia volatilisation losses following the land application of livestock manures can be elevated, particularly for high readily available N manures where they are not rapidly soil incorporated after application.
- Nitrous oxide emissions of *c*.1.96% of the readily available N remaining after ammonia loss have been measured following livestock manure additions to land (Thorman *et al.* 2006), with emissions following a typical livestock manure application (at 250 kg/ha total N) estimated to be equivalent to 0.18-0.73 t CO_2e/ha (Bhogal *et al.,* 2007). However, if inorganic fertiliser N rates are reduced to account for the crop available N supplied by the livestock manure, there will be a reduction in N_2O emissions from this source.

Method 11. Import materials high in organic carbon

Description: Increase SOM levels through the addition of carbon rich materials such as green and green/food compost, biosolids (treated sewage sludge), paper crumble, mushroom compost, water treatment cake, industrial 'wastes' etc. There has also been increasing interest in the potential use of Biochar (produced by the pyrolysis of crop residues/biomass) as a means of increasing soil C storage and improving soil structure and fertility (Lehmann, 2007), although the use of this material for improving SOM levels should currently be considered 'speculative'.

Potential for applying the method: The method can be applied to all types of cropping systems provided that regulatory rules are adhered to. There are several Codes of Practice and pieces of legislation that seek to 'control' the application of these materials to agricultural land e.g. The Water Code (MAFF, 1998), Nitrate Vulnerable Zones (NVZs) Action Programme (Defra, 2002a), The Sludge (Use in Agriculture) Regulations (SI, 1989 & 1990), the Waste Framework Directive (91/156/EEC amending 75/442/EEC) and recently introduced Cross Compliance measures and associated Statutory Management Requirements. In particular in NVZs, the application of organic materials should not exceed the field rate limit of 250 kg/ha total N per annum (Defra/EA, 2008).

Products arising from 'waste' sources, such as green and green/food compost, cease to be classified as waste (i.e. are no longer subject to the control mechanisms within the Waste Framework Directive) once they have been fully recovered. The Compost Quality Protocol sets out criteria for the recovery/production of quality compost from source segregated biodegradable waste, which includes compliance with PAS 100 for composted materials (BSi PAS 100). Non-adherence to the Quality Protocol (WRAP and Environment Agency, 2008) will result in the compost being considered to be a waste and subject to waste management controls. In these cases, an exemption from the Environmental Permitting regulations may be obtained from the Environment Agency, if land treatment is for 'agricultural benefit or ecological improvement'.

Biosolids applications are subject to the "Sludge Use in Agriculture Regulations" which set out legal obligations for both biosolids suppliers and farmers. There are a number of restrictions associated with the use of biosolids that are detailed in the ADAS "Safe Sludge Matrix". The regulations restrict the potential use of this material, particularly in vegetable and grassland cropping systems.

At present over 1.1 million tonnes of green and green/food compost and *c.*700,000 tonnes of paper crumble are currently recycled to agricultural land (Association for Organics Recycling, 2008; Gibbs *et al.,* 2005); such applications are only presently made to relatively small areas of land (<50,000 ha). However, compost use on agricultural land is expected to increase at least 2-3 fold over the next decade. Despite this predicted increase, limited supplies of some 'land ready' sources of carbon rich materials (e.g. green compost and paper crumble) could restrict the widespread application of this method.

Practicality: These organic materials may be applied to land using equipment that is currently used for the application of solid livestock manures. However, without further 'land ready' sources of these organic additions, supply is likely to limit the practical application of this method.

Likely uptake: Initial uptake is likely to be low, especially for the more novel sources of organic matter additions such as paper crumble (and Biochar). The regulatory and record keeping requirements associated with compost application and/or the necessity to seek exemption from Waste Management Licensing Regulations, may also provide a barrier to the likely uptake of this method.

Costs: The application of organic materials is likely to be at least cost neutral and most probably will result in cost savings (due to potential savings in inorganic fertiliser use).

Carbon storage effectiveness: Results from the Woburn 'classical market garden experiment' (Johnston, 1975). and the "Long-term Sludge Experiments" (Gibbs *et al.*, 2006) show that the application of biosolids to agricultural soils in Britain has the potential to increase SOM by 180 kg C/ha/yr per tonne of digested sludge (ds) applied (with 95% confidence intervals in the range 130-230 kg/ha/yr/t ds; Bhogal *et al*., 2007). For green compost, results from four Enviros study sites (Wallace, 2005; 2007) indicate that the application of green compost to agricultural soils in England has the potential to increase SOM by 60 kg C/ha/yr per tonne compost dry solids applied (95% CI in the range 36-84 kgCha/yr/t ds; Bhogal *et al*., 2007). Bhogal *et al.* (2007) considered that the broad composition of carbon compounds within paper crumble was similar to livestock manures, and hence used livestock manure data to estimate C accumulation in soils following the application of paper crumble i.e. 60 kg C/ha/yr/t dry solids applied.

At typical application rates (250 kg/ha total N for compost and biosolids, 75t/ha for paper crumble), a total of 1.4, 1.5 and 1.8 t C/ha/yr could be retained in the topsoil following the application of compost, biosolids and paper crumble, respectively (Bhogal *et al*., 2007). This is equivalent to 5.1-6.6 tCO_2e/ha and equates to *c*.1.5% of the typical carbon content of an arable soil in England and Wales (*c*.91t/ha, assuming 28 g/kg soil OC, 1.3 g/cm^3 bulk density and 25 cm soil depth; Webb *et al.,* 2001). However, this can only be regarded as the initial rate of SOM increase (up to *c.*20 years), as SOM accumulation rates decline with time.

Other costs and benefits:

- The application of C-rich organic materials (particularly composts and biosolids) can provide a valuable source of plant available nutrients, particularly nitrogen (N) phosphorus (P), potassium (K), sulphur (S) and magnesium (Mg), thereby reducing the need for inorganic fertiliser inputs; and usually result in financial savings to the farmer. However, compensatory inorganic fertiliser N is required following the application of chemically/physically treated paper crumble (because of N immobilisation), to ensure crop yields are not compromised (Gibbs *et al.* 2005).
- A reduction in inorganic fertiliser will result in energy consumption savings involved in manufacturing inorganic fertilisers (particularly N), estimated at *c.*0.1tCO_2e/ha from a typical biosolids application (Bhogal *et al.,* 2007).
- The application of organic materials also presents a risk of environmental pollution, *if not handled and managed carefully*. Applications therefore need to be managed to limit N losses by NH_3 volatilisation and N_2O emission to air, and NO_3, P and FIO losses to water.
- The repeated application of biosolids and composts may lead to the build of heavy metals in the soil.
- Materials high in organic C help to maintain soil structure and aggregate stability, which in turn can increase soil water retention and water infiltration rates (thereby reducing the risks of soil erosion) and improves plant nutrient uptake.

3.5. CATEGORY E: SPECULATIVE METHODS

The review of current literature (Table 1) identified a number of additional methods that could potentially maintain or enhance SOM (Table 2). However, these were largely speculative, with many based on established theories of SOM turnover (and controlling factors), rather than robust experimental evidence. The methods were therefore deemed to be insufficiently robust to promote to farmers/land managers without further investigation. A brief summary of the rationale underpinning each of the proposed methods is given below, with supporting data where available.

Method 12. Convert to organic farming systems

Organic farming relies on the management of SOM to enhance soil fertility (Watson *et al.,* 2002). Therefore, by definition, an increase in SOM would be expected. The benefit is largely perceived to be a result of the use of fertility building grass or clover leys (method 4), cover crops/green manures (method 8) and greater reliance on organic manures (method 10) (Stockdale *et al.,* 2001). There is conflicting evidence on the benefits of organic systems to SOM levels, with some reports suggesting an increase, while others have reported no change (e.g. Gosling & Shepherd, 2005). It has been suggested that OC inputs in organic systems may be of a different 'quality' to those in conventional systems, which may confer a greater benefit to SOM. For example, Marriot and Wander (2006) found that soils under organic management contained more particulate OM, with a lower C:N ratio, than in soils from conventional systems. However, it has been suggested that higher yields in conventional systems (and hence crop residue returns), the rapid decomposition of green manures/cover crops/fertility building leys in organic systems (due to low C:N ratios) and similar manure inputs, result in no additional benefit of an organic system compared to its conventional counterpart (Gosling & Shepherd, 2005).

Method 13. Extensification of pig and poultry systems onto arable land.

Transferring a proportion of the national housed pig herd and poultry flock to outdoor units set up on temporary (typically 2 year) ley grassland in arable areas has been suggested to potentially increase SOM levels (King *et al.,* 2004). As in method 4, SOM would potentially be increased by introducing rotational grass for 2 years (or more) in a 6 year rotation, thereby reducing the frequency of tillage operations. There may also be an additional benefit from the input of excreta deposited on the ley (method 10). However, as detailed in method 4, the benefits to C storage of introducing short-term grass leys into arable cropping systems are questionable, with conflicting evidence, due to uncertainty over how increases in SOM from the 2 year ley will be maintained over the long-term. Soil damage and erosion losses from outdoor pig production, in particular, can be very pronounced and there is likely to be an increased risk of diffuse pollution (particularly via NO_3 leaching and P/FIO losses in surface run-off).

Method 14. Place OM deeper in soil

Placing organic matter inputs deeper into the soil could reduce decomposition rates (colder temperatures) and protect against erosive losses (Dawson & Smith, 2006). However, there is no supporting experimental evidence for this method, with most methods of deep incorporation likely to increase soil disturbance and hence aeration and decomposition rates.

Method 15. Use clover in grassland (mixed sward)

In a survey of French grassland soils, Sousanna *et al* (2004) showed that grassland management strongly affected SOM levels. Using a combination of measurements and modelling, annual C storage rates of between 0.2 and 0.5 t C/ha/yr (0.7-1.8 t CO_2e/ha/yr) were estimated to result from changes in forage production. These were largely a consequence of reducing N fertiliser inputs to highly intensive grass leys, increasing the duration of grass leys, converting pure grass leys to grass-legume mixtures and moderately intensifying nutrient poor permanent grasslands. In a review of 115 studies worldwide, Conant *et al*. (2001) also showed that improvements in grassland management can lead to increases in soil C storage in the range 0.1-3.0 t C/ha/yr (0.03-11 t CO_2e/ha/yr), with a mean of 0.5 t C/ha/yr (1.8 t CO_2e/ha/yr). The management practices included fertilisation, improved grazing management and sowing legumes, and were largely associated with improvements in forage production (and hence C inputs). UK studies included within the review were largely from extensive, upland grassland systems (e.g. Bargett *et al.,* 1993), where improvements in grassland nutrition and productivity (e.g. by the inclusion of clover) were likely to be responsible for measured increases in SOM levels. In contrast, King *et al*. (2004) suggested such studies (i.e. in extensive upland systems) were not relevant to managed grassland soils in the UK, and therefore assumed there would be no direct C storage benefit from greater use of clover in UK grasslands (only an indirect benefit due to an energy saving from reduced fertiliser N use).

Method 16. Reduce use of lime on grasslands and organic/peaty soils

Many organic/peaty soils are naturally acidic (pH<5.0) and this is generally considered to limit the microbial activity of decomposer organisms, which favour a neutral environment, aiding the build up of SOM (Scottish Executive, 2007). Decreasing the use of lime on grassland and high in organic matter (i.e. organic and peaty) soils, could therefore potentially increase SOM levels, by reducing decomposition rates. Experiments have shown that liming can increase the concentrations of organic matter and DOC (dissolved organic carbon) in soil drainage waters with the impact greatest in the pH 4 to 5 range (Scottish Executive, 2007). Persson and Wiren (1989) reported that increasing the acidity of forest soil from pH 3.8 to 3.4 reduced CO_2 production by 83%, and from pH 4.8 to 4 by 78%. This suggests that increasing the pH of naturally acidic soils by the addition of lime will increase CO_2 emissions and reduce soil OC stocks. This is supported by a study on an upland grassland, which showed that liming caused more rapid C turnover (Rangel-Castro *et al*., 2004). Soil pH may have a varying impact depending on aeration and water logging. For example, Bergman *et al.* (1999) compared CO_2 production rates at pH 4.3 and 6.2, and found that under anaerobic conditions rates were 21-29 times greater at the more neutral pH (depending on temperature), while under aerobic conditions rates were 3 times greater at 7◦C on the neutral pH soil, but soil pH had no significant effect at 17◦C. This suggests that liming will have a greater impact on SOM levels on wet organic soils.

Method 17. Minimise fertiliser use on organic soils

Fertilisation is generally considered to increase SOM levels in mineral soils, due to increased residue returns (method 9). In organic soils, however, this assumption may not hold true. The added nutrients, combined with aerobic conditions, can accelerate organic matter decomposition and increase CO_2 emissions (Byrne *et al*., 2004). This effect may be particularly enhanced where lime is also applied (see Method 16), making conditions more favourable for decomposition, as well as supplying extra nutrients. SOM decomposition rates on organic soils could therefore be reduced by minimising fertiliser use and to a lesser extent by timing fertilisation to coincide with periods of greatest crop growth when best use can be made of the applied nutrients.

4. BEST PRACTICES FOR MANAGING SOM IN 'LOWLAND' AGRICULTURE: CONCLUSIONS & KNOWLEDGE TRANSFER

This review has identified at least 11 practices (methods) for managing SOM in 'lowland' agriculture (Table 2), and provided a largely qualitative comparison of their relative benefits (to SOM and C storage), costs, practicality and environmental impacts across a range of soil types (Table 3). The methods were broadly divided into those which aimed to protect and maintain existing SOM levels for their soil quality and fertility benefits (e.g. reduced soil erosion, changed tillage practices and increased organic matter additions), with the potential added benefit of enhancing SOM, compared with more extreme measures (such as permanent land-use change), whose ultimate goal was to increase soil C storage. The latter (category A in table 2) have been identified as having the *greatest potential* for increasing SOM (and hence soil C storage and overall carbon savings). However, many would involve an extreme change in the way agricultural land is currently managed (contrary to the requirement for food and fibre production) and would require changes at policy level for widespread implementation, with suitable financial incentives.

The division of methods in this manner is compatible with the way agricultural production is currently regulated and incentivised via Cross Compliance measures and Environmental Stewardship (ES). Cross Compliance requires farmers to maintain soils in Good Agricultural and Environmental Condition (GAEC) and comply with certain Statutory Management Rules in order to be eligible for the Single Payment Scheme (Anon., 2006b). Preparation of a Soil Protection Review is a key requirement and identifies ways in which soils will be managed to maintain SOM and soil structure, and minimise erosion. The methods identified in categories B-D (methods 6-11), whose aim is largely to protect and maintain SOM levels, would therefore most naturally be promoted by this route. It is also this group of methods that could be used either singularly or in combination to achieve added benefit, depending on the situation and overall goal (e.g. increasing organic inputs via cover crops, manures or other organic materials could quite readily be employed with many of the erosion control methods on the same unit of land).

Environmental Stewardship (ES) aims to deliver improvements in biodiversity, landscape, protection of the historic environment and natural resources. Entry Level Stewardship (ELS) is open to all farmers, but Higher Level Stewardship (HLS) is actively targeted at land of particular environmental value and is a competitive scheme in which only those assessed as delivering the best outcomes are selected. It will also only incorporate methods where there has been income forgone by the farmer. To this end, methods in category A (land-use change) would be best promoted by this route.

Besides incorporation into current Cross Compliance Rules or Environmental Stewardship, these methods should also be promoted via the provision of farmer advice (e.g. alongside the England Catchment Sensitive Farming Delivery Initiative) and included within the Code of Good Agricultural Practice.

5. RECOMMENDATIONS FOR FUTURE WORK

- There would be value in confirming, via field measurements (under UK conditions) the C storage/saving benefits of many of these methods, and the effect of soil type. This is particularly important to those methods proposed in category A (land use change), which have been identified as (probably) offering the greater potential for soil C storage/savings on agricultural land. And similarly, there would be value in quantifying C emissions following the ploughing out of grassland, as regularly occurs at reseeding in ley/arable rotations, or where a farm converts from grassland to tillage crop production or from grassland to maize growing (as commonly occurs on dairy farms that have either stayed in milk production, via maize growing, or have given up milk production to grow combinable crops).
- There is a need to continue existing long-term field studies (e.g. The "Long-term Sludge Experiments", "SOIL-QC" and the classical experiments at Rothamsted) to evaluate the effects of SOM management methods on soil carbon storage and soil function, along with overall impacts on soil quality/fertility, agricultural productivity and wider impacts on the environment (e.g. water and air quality).
- Nitrous oxide is a powerful greenhouse gas, with a global warming potential that is 310 times that of CO_2. Due to increased soil wetness and reduced aeration, there is the potential for increased N_2O emissions following zero and probably reduced tillage, which could completely offset any CO_2-C saving achieved due to increased SOM levels, although the evidence for this is currently unclear. There is therefore a need to establish unequivocally whether reduced/zero tillage practices increase N_2O emissions (compared with conventional tillage), the amounts emitted and the factors affecting losses. This will help underpin the development of 'smart' N_2O emission factors currently being derived in Defra project AC0101.
- The oxidation and erosion of 'lowland' organic soils has been identified as a major contributor to the decline in SOC in UK topsoils. Further research on the impact of raising the water table in these regions on SOC and the overall balance of GHG emissions is required.
- Subsoil (> 30cm) C storage and dynamics is poorly understood. Further research on the impact of agricultural management practices (particularly subsoiling) on subsoil C storage is required.

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1. Invitation

BEST PRACTICES FOR MANAGING SOIL ORGANIC MATTER IN AGRICULTURE

Tuesday 17th March 2009
10am– 4pm
Chemical Industries Association,
Kings Buildings, Smith Square, London

On behalf of Defra, we would like to invite you to participate in the above workshop on best practices for managing soil organic matter in agriculture. Protecting and enhancing SOM levels is a key objective of Defra's proposed Soil Strategy because of the beneficial effects for overall soil quality/fertility, carbon storage and erosion control. This workshop aims to draw together scientists and practitioners with expertise in the management of soil organic matter to review and advise on best practices for inclusion in revised soil management guidance in England. The workshop will be divided into two key sessions in order to consider practices most appropriate for 'lowland' and 'upland' agriculture (draft agenda attached). As well as identifying best practice, the workshop will discuss the relative costs and benefits of each measure and explore how the results can be translated into advice for farmers and land managers, and incorporated into current Cross Compliance Guidance for Soil Management or via incentivised Environmental Stewardship.

Please could you confirm (by 6th March) whether you are able to attend this meeting, which session you hope to attend (lowland/upland/both) and whether you will require lunch.

With kind regards

Yours sincerely

Anne Bhogal
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2. Agenda

BEST PRACTICES FOR MANAGING SOIL ORGANIC MATTER IN AGRICULTURE

Tuesday 17th March 2009: 10am– 4pm; Chemical Industries Association, Kings Buildings, Smith Square, London

Draft Agenda

10:00 am Coffee

10:15 am Managing SOM in 'lowland' agriculture (land below the intake wall/fence)

Policy introduction (Judith Stuart, Defra)

Best Practice for lowland agriculture (Anne Bhogal, ADAS)
- Land use change
- Tillage
- Erosion control
- Organic inputs
- Other

Discussion (all)
- Are these methods appropriate, effective and achievable?
- Under which conditions (soil and farm types) are these methods most suitable?
- Any gaps?
- How can these methods be translated into advice for farmers & incorporated into Cross Compliance Guidance or Environmental Stewardship?

1:00 pm Lunch

2:00 pm Management SOM in 'upland' agriculture (land above the intake wall/fence)

Policy introduction (Judith Stuart, Defra)

Best Practice for upland agriculture (Fred Worall, Durham University)

Discussion (all)
- Are these methods appropriate, effective and achievable?
- Under which conditions are these methods most suitable?
- Any gaps?
- How can these methods be translated into advice for farmers & incorporated into Cross Compliance Guidance or Environmental Stewardship?

3.30 pm Close & tea

3. List of delegates

Name	Affiliation
Anne Bhogal	ADAS
Fiona Nicholson	ADAS
Andy Whitmore	Rothamsted Research
Graham Merrington	WCA Environment
Matthew Shepherd	Natural England
Derek Holliday	CLA
Morag Cuthbert	Defra
Claire Denniss	Defra
Judith Stuart	Defra
Fred Worrall	Durham University
John Kay	National Trust
Nathan Morris	TAG
Aarun Naik	NFU
Ruben Sakrabani	Cranfield University
Madeline Bell	Durham University