General enquiries on this form should be made to:
Defra, Science Directorate, Management Support and Finance Team,
Telephone No. 020 7238 1612
E-mail: research.competitions@defra.gsi.gov.uk

## SID 5 Research Project Final Report

### Note

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<table>
<thead>
<tr>
<th><strong>Project identification</strong></th>
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<tr>
<td>1. Defra Project code</td>
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<td>2. Project title</td>
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<td>3. Contractor organisation(s)</td>
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| **54. Total Defra project costs** | £ 54,138 |
| **5. Project:** | **start date:** 01 July 2006 | **end date:** 28 February 2007 |
6. It is Defra’s intention to publish this form. Please confirm your agreement to do so.

YES ☐ NO ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a “No” answer.

In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Environmental Stewardship (ES) was launched to build on the already successful Environmentally Sensitive Areas (ESA) scheme and the Countryside Stewardship Scheme (CSS). The current objectives of Environmental Stewardship (ES) within England include the protection of soil and water, the enhancement of biodiversity and resource protection. For land within an ES agreement the land owner receives an area payment to compensate for any income foregone incurred (for example a reduction in or loss of crop yield or an increase in management costs) to a maximum 100%. The alterations to the land use and management practices as a result of management within ES may also have implications for climate change mitigation.

An increase in the global mean temperature as a result of increased retention of thermal radiation by the Earth’s atmosphere, has raised concern over global warming and the uncertainty this may have with respect to future impacts on the climate. Climate change has been addressed globally by the Framework Convention on Climate Change (FCCC) at the Earth Summit of 1992, then by the Kyoto Treaty of 1997. In response to the World Summit on Sustainable Development (WSSD) (2002) a number of key policy documents including Changing Patterns - the UK Government Framework for Sustainable Consumption and Production (2003), Delivering the Essentials of Life – Defra’s Five Year Strategy (2004) and Securing the Future - UK Sustainable Development Strategy (2005) were produced. The Kyoto Treaty commits industrialised nations to a reduction in greenhouse gas (GHG) emissions, in particular Carbon Dioxide (CO₂), by 5.2% below their 1990 levels during the first commitment period, the Quantified Emission Limitation or Reduction Commitments (QELRC), between 2008 and 2012. The EU is required to collectively reduce GHG emissions by 8% while the UK target is a 12.5% reduction. The UK GHG emissions in 2005 were 15.3% below 1990 levels although much of the decrease between 2004 and 2005 was due to a 4.6% reduction in emissions from the domestic sector. The UK has its own target to reduce emissions by 20% in 2010, 20 - 32% by 2020 and 60% by 2050 outlined in Climate Change The UK Programme.

Carbon dioxide is one of six main GHGs known to act as a barrier to thermal radiation. Others include nitrous oxide (N₂O), methane (CH₄) Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). Each of the GHGs listed has a different potential to cause global warming but may be standardised on a single scale as t
agriculture was responsible for 52.62 MT CO₂ e, 8.2% of the UK’s GHG emissions (excluding Land Use Change and Forestry), 37.5% of its methane emissions and 68.0% of its nitrous oxide emissions. Within agricultural systems, the main sources of GHG emissions are from:

1. CO₂ released from burning fossil fuel (7.102 MT CO₂ e from UK agriculture in 2005 (13.5% of UK agricultural emissions) either during (a) product manufacture (of pesticides and fertilisers), their packaging and transport (to farm); (b) application by spraying or spreading or fuel consumed by tillage operations and drilling; (c) indirect energy (fuel consumed during machinery manufacture and calculated based on depreciation per operation). Carbon dioxide is also released from high C containing organic (peat) soils (for example lowland raised bog and fen habitats) during decomposition under aerobic conditions following land drainage.

2. N₂O released from soils and from livestock manures and during the manufacture of nitrate fertiliser (26.961 MT CO₂ e from UK agriculture in 2005 (51.2% of UK agricultural emissions).

3. CH₄ released from ruminant animals and from livestock manures (18.561 MT CO₂ e from UK agriculture in 2005 (35.3% of UK agricultural emissions).

The method used serves as a guide to the potential impact that ES may have on GHG emissions, both positive and negative, within the UK relative to previous methods of land management. A baseline set of management conditions has been defined in order to provide a reference point against which any changes in land management under ES may be compared. The following require consideration:

1. It is acknowledged that the results would benefit from an uncertainty analysis to account for spatial variability and the impact different soil types, increased or decreased rainfall and variation in the farming practices defined within the baseline conditions may have on the calculated change in emissions for each option. Such variations would further add to the accuracy of the results that have been aggregated to the national scale based upon the uptake of each option. An uncertainty analysis was not possible within the project time-scale and typical scenarios have been constructed as far as possible. It must be emphasised that the method uses average figures and the calculations serve as a guide to allow a comparison between options.

2. The results do not account for a displacement in production within the calculated GHG balance. This may be firstly, the impact of producing and importing the same agricultural commodity from another country to replace any commodity where production has been reduced as a consequence of converting the land into an ES agreement. It is estimated that the UK is currently 72% self-sufficient for the agricultural commodities it is capable of producing itself. The removal of a proportion of productive agricultural land within England as a consequence of the undertaking of ES agreements may displace that production outside of the UK. At the time of writing the impact of imported agricultural goods on GHG emissions reported by previous analyses had been concluded to be insufficiently robust to allow a direct like for like comparison. In response an analysis of the impact of UK versus overseas supply chains is currently the subject of Defra Project FO0103, the results of which are not available at the time of writing. Not all ES options necessitate that a reduction in production occurs but it is recommended that it be taken into account where applicable as and when suitable data becomes available. Secondly, displacement may occur on the same farm whereby output is increased within other areas of the same farm that in turn neutralises or reduces any potential reduction in GHG emissions from the specified change of land management. Displacement of production onto other farms in U.K. would have a similar effect. Displacement of production overseas may reduce the U.K. GHG inventory without necessarily reducing global GHG emissions. Inventorisation of altered emissions, i.e. whether amended emissions would be captured by current inventory methodology, is not covered in this report.

For most of the options within ES a reduction in the GHG emissions (excluding displaced production (EDP)) relative to the baseline management scenario has been calculated. This decrease arose from two mechanisms, the first of which was a reduction in the source of emissions (permanent CO₂ e savings(EDP)). The main source of these emissions in the baseline scenarios considered were the use of inorganic N fertiliser, N₂O emissions from soil, fossil fuel consumption from the use machinery (in particular deeper tillage operations and the transportation of bulky materials), CH₄ from the enteric fermentation of livestock and CH₄ and N₂O emissions from livestock manures. The second mechanism by
which CO₂e savings_{(EDP)} were made through ES were non-permanent and resulted from an increase in the C stored within the land when at equilibrium either as soil organic carbon (SOC) or above ground carbon (AGC) relative to the baseline scenario. The accumulation of C does not occur over an indefinite period and stops upon reaching the equilibrium, which is determined by the method of land management. Any C gained may potentially be lost to the atmosphere if the original management regime is re-instated. This is temporary and may potentially be lost should the land management be altered such that it is not conducive to C sequestration, for example the removal of trees or the ploughing of the soil. The main factors that determined the ranking of options by the greatest to least CO₂e savings_{(EDP)} could be grouped as:

1. a permanent change in land use from an arable or improved grassland baseline to a management scenario with virtually zero inputs (fertilisers, pesticides and the use of machinery to plough the land). The land was no longer ploughed and the CO₂e savings_{(EDP)} were increased due to the accumulation of additional C within the soil (and potentially above ground), a reduction in fuel consumption from the manufacture of agro-chemical products and their application, a reduction in the N₂O from soil and a reduction in emissions of CH₄ from livestock. The change in the GHG balance_{(EDP)} of this group of options relative to the baseline ranged between -17.5 to -5.4 t CO₂e ha⁻¹ year⁻¹. The contribution of accumulated SOC to this change was typically between 3.3 and 4.0 t CO₂e ha⁻¹ year⁻¹ on cultivated land and improved grassland respectively. The increase in AGC was smaller, 0.7 - 2.9 t CO₂e ha⁻¹ year⁻¹ respectively during the first year after the change in management only. The remainder of the reduction in the GHG balance_{(EDP)} arose from a decrease in emissions associated with the manufacture of agro-chemicals, fuel to conduct field operations and emissions of N₂O from soil. The removal of livestock or a reduction in stocking rates reduced the emissions of CH₄ from enteric fermentation and manures. Options within this category included the creation of grass buffer strips on cultivated land or improved grassland and several of the habitat creation options within the HLS. Also included within this category was the restoration or creation of habitats on peat soils where management involved the re-wetting of the soil.

2. arable land with a reduction in inputs and that was managed such that C accumulation occurred within the soil but at a lower rate than the previous category and established an equilibrium at a lower SOC content. The GHG balance_{(EDP)} of this group of options relative to the baseline was reduced by between −3.3 and −1.8 t CO₂e ha⁻¹ year⁻¹. The contribution of accumulated SOC to this change ranged from 0.2 to 2.6 t CO₂e ha⁻¹ year⁻¹. A reduction in fuel consumption and emissions of N₂O from soil also occurred but were not of the same magnitude as found in category 1 since inputs of agro-chemicals were permitted although restrictions were stipulated. An example is the inclusion of a grass / clover crop within the rotation required by the option to undersow spring cereals.

3. land that remained within its original use with no alteration to the SOC or AGC content (cultivated land remained cultivated without practices listed in category 2, improved grassland remained ploughed and re-seeded, semi-natural / unimproved land was not ploughed). A reduction in the GHG balance_{(EDP)} (-0.8 to 0 t CO₂e ha⁻¹ year⁻¹) arose solely from decreased gaseous emissions since there was no alteration to the SOC or AGC equilibrium. There was a restriction on the quantity and / or timing of the application of inputs of fertilisers or pesticides, or a reduction in stocking rates and permanent CO₂e savings_{(EDP)} from a reduction in fuel consumption, emissions of N₂O from soil and CH₄ from livestock enteric fermentation and manures.

4. options that increased the CO₂e emissions to the atmosphere through an initial loss of vegetation and AGC from, for example, scrub removal. An increase in the mean GHG balance_{(EDP)} of up to 0.73 t CO₂e ha⁻¹ year⁻¹ after 5 years was estimated. Over time the increase in emissions tended to be neutralised from decreased fuel consumption. Another example was the introduction of livestock on previously ungrazed land as part of a habitat management plan although the stocking rates and thus the increase in GHG emissions_{(EDP)} tended to be low.

The current study has estimated the potential GHG mitigation_{(EDP)} properties of each option after periods of 1, 5, 25, 50 and 100 years assuming there was not reversion to other management during this time although in reality this may be difficult to implement unless long term agreements are undertaken. Overall, excluding any contributions to climate change from displaced production, Environmental Stewardship (with addition of the equivalent options from the Countryside Stewardship Scheme (CSS) and the Environmentally
Sensitive Areas (ESAs)) was calculated to reduce CO$_2$e emissions to the atmosphere by between 0.44% and 0.49% of the 1990 Kyoto baseline after between one and 100 years. The options at their current levels of uptake are predicted to peak in their climate change mitigation potential as a reduction of a proportion of annual UK GHG emissions after between 5 and 50 years. No further decrease occurred after this time on account of the SOC sequestered in options that create for example, semi-improved grassland on arable land (equilibrium established after 45 years) or unimproved grassland or grass strips on improved grassland (39 years) remaining constant. The reduction in the proportion of total UK GHG emissions declined as the options continued to reduce permanent emissions from reduced inputs but not the temporary CO$_2$e savings from sequestration. Post year 50 this became more apparent due to no further SOC accumulation in options that created unimproved grassland or grass strips on arable land (55 years) or AGC accumulation in the form of tree growth.

Priority recommended practices and modifications to existing options

Many of the stipulated management requirements within the first category of ES options are conducive with minimising the GHG balance of each option and there is little scope for further reductions without compromising option objectives since current inputs are practically zero. Where land within ES is completely removed from agricultural production or is not currently within production a number of priority recommended practices are applicable in combination to minimise the GHG balance of the land:

1. no fertilisers (eliminate fuel consumption and reduce soil N$_2$O emissions)
2. no soil cultivation (eliminate fuel consumption and allow the SOC at equilibrium to be maximised)
3. minimal use of cutting or mowing (reduce fuel consumption and maximise the AGC at equilibrium)
4. no / targeted application of pesticides (reduce fuel consumption)
5. no grazing (eliminate fuel consumption from supplementary feed production, CH$_4$ from enteric fermentation, CH$_4$ and N$_2$O emissions from livestock manures, maximise the AGC at equilibrium)
6. the restoration of the water table on peat soils (prevent further loss of C from the soil)
7. the ‘gapping up’ and the ‘planting of new / restoration of hedgerows’ on existing field boundaries (increase the C stored in plant biomass)

Environmental Stewardship makes an important contribution to the preservation and restoration of peat soils where large quantities of C are stored. To maximise the C sequestration potential of options within ES the habitat maintenance, restoration and creation options should preferably be offered for longer-terms than the 5 and 10 years currently within ELS and HLS agreements respectively.

Where land is maintained within production (not accounting for yield and thus displacement of production elsewhere) modifications to existing options that may reduce the GHG balance further while not compromising option objectives include:

1. further restrictions of N applied to cultivated land where minimal or zero tillage is stipulated to achieve option objectives or combine with existing lower N input options for cultivated land (reduce risk of soil N$_2$O emissions)
2. use of wild flower or birdseed mixtures that permit a greater period between re-establishment (enhance the accumulation of SOC on existing cultivated land or reduce its loss on improved grassland)
3. chop and spread the straw so it can be incorporated into the soil upon establishment of the crop following winter stubbles (enhance the accumulation of SOC)
4. account for N, P and K from the deposition of grazing livestock in the fertiliser recommendations to the crop following forage crops.
5. apply farmyard manure (FYM) to cultivated land as opposed to grassland or land where there is infrequent tillage such as orchards (enhance the accumulation of SOC)
6. substitute fertiliser N with clover on permanent grassland (reduce emissions from product manufacture and risk of soil N$_2$O emissions)
7. no application of N to wet peat soils (reduce risk of N$_2$O emissions from soil)
8. further restrictions of N applied to land that may be waterlogged during the year (reduce risk of N$_2$O emissions from soil)
9. stipulate no inputs to any uncropped areas (for example skylark plots)

**Future work.**

The emission factors from the manufacture of products and their application have been derived from life-cycle analyses and have been used with a high degree of confidence. The emissions of \(N_2O\) from soil and the quantity of \(C\) accumulated in the soil and above ground vegetation have a potentially greater impact but are subject to a number of variables characteristic of a particular location such as soil type and annual rainfall. A regional analysis could take these variables into account to a greater degree to establish if certain options offer greater climate change mitigation potential within different regions. The accounting for emissions associated with the displacement of production when appropriate data becomes available would also benefit the study.

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**Project Report to Defra**

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1.0. ABSTRACT OF THE RESEARCH PROPOSAL

1.1. In March 2005 the UK Government launched ‘Securing the Future – UK Government sustainable development strategy’, a component of which is ‘sustainable production and consumption’. In addition, the Department for Environment, Food and Rural Affairs (Defra) launched its five year strategy ‘Delivering the Essentials of Life’ that addressed its vision of sustainable rural communities within the UK being economically and environmentally viable, and socially inclusive. The ‘Rural Development Programme for England 2007-2013’ that was under consultation between April and July 2007 aims to help farmers manage land in a more sustainable way including a reduction in the impact on climate change. It will increase the funding available for Environmental Stewardship (ES). This project, with its focus on the
potential for greenhouse gas (GHG) mitigation by ES within England, supports the UK Sustainable Development Strategy and a Defra Strategic Priority4 ‘Climate change and energy’, with reduced GHG emissions one strategic outcome. Environmental Stewardship was launched to build on the already successful Environmentally Sensitive Areas (ESA) scheme and the Countryside Stewardship Scheme (CSS). For land within an ES agreement the landowner receives a payment to compensate for any income foregone incurred (for example a reduction in or loss of crop yield or an increase in management costs) to a maximum 100%. The current objectives of ES include the protection of soil and water, the enhancement of biodiversity and resource protection. The alterations in land use and land management that an ES agreement requires may also have implications for climate change mitigation.

1.2. an increase in the global mean temperature as a result of increased retention of thermal radiation by the Earth’s atmosphere, has raised concern over global warming and uncertainty over future impacts on the climate5,6. Climate change has been addressed globally by the Framework Convention on Climate Change (FCCC) at the Earth Summit of 1992, then by the Kyoto Treaty of 1997. The Kyoto Treaty commits industrialised nations to a reduction in GHG emissions, in particular carbon dioxide (CO₂), by 5.2% below their 1990 levels during the first commitment period, the Quantified Emission Limitation or Reduction Commitments (QELRC), between 2008 and 2012. The EU is required to collectively reduce GHG emissions by 8% while the UK target is a 12.5% reduction7. The UK GHG emissions in 2005 were 15.3% below 1990 levels although much of the decrease between 2004 and 2005 was due to a 4.6% reduction in emissions from the domestic sector8. The UK has a target to reduce its emissions by 20% by 2010 and 60% by 20509.

1.3. Carbon dioxide is one of six main GHGs known to act as a barrier to thermal radiation6. Others include nitrous oxide (N₂O), methane (CH₄) Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). Each of the GHGs listed has a different potential to cause global warming but may be standardised on a single scale as eq t CO₂e, its global warming potential (GWP).

Within agricultural systems, the main sources of GHG emissions are from:

1. CO₂ released from burning fossil fuel (7.102 MT CO₂e from UK agriculture in 20055 (13.5% of UK agricultural emissions) either during (a) product manufacture (of pesticides and fertilisers), their packaging and transport (to farm); (b) application by spraying or spreading or fuel consumed by tillage operations and drilling; (c) indirect energy (fuel consumed during machinery manufacture and calculated based on depreciation per operation). Carbon dioxide is also released from high C containing organic (peat) soils (for example lowland raised bog and fen habitats) during decomposition under aerobic conditions following land drainage5. 

2. N₂O released from soils and from livestock manures and during the manufacture of nitrate fertiliser (26.961 MT CO₂e from UK agriculture in 20055 (51.2% of UK agricultural emissions).

3. CH₄ released from ruminant animals and from livestock manures (18.561 MT CO₂e from UK agriculture in 20055 (35.3% of UK agricultural emissions).

1.4. Environmental stewardship options may include a reduction in or the elimination of for example fertilisers, pesticides and cultivations which will potentially impact upon climate change through a reduction in the GHG emissions5,6 associated with their manufacture and application. These options may also require that the land is removed from agricultural production and this risks the displacement of that production elsewhere, either on the same farm or outside of the UK. The importance of energy conservation and mitigating climate change in the UK was highlighted in the Energy white paper: our energy future - creating a low carbon economy8 and more recently the Energy white paper: meeting the energy challenge published in 200710. Further pressure to maximise overall energy efficiency coupled with reduced dependence upon fossil fuels has arisen in light of estimations that a peak in oil supply is imminent11. In addition to the reduction in GHG emissions through alternative management strategies, it may be possible to increase the carbon (C) stored within the soil, the soil organic content (SOC) or above ground, the above ground C (AGC). The SOC and AGC may be increased by a change in land management such as conversion of cultivated land to woodland or grassland, the incorporation of organic manures or through reduced tillage12,13,14,15,16. A major barrier to successful agricultural GHG mitigation has been cited as ‘transaction costs’ whereby farmers will not adopt otherwise profitable agricultural GHG mitigation practices in the absence of policies or incentives17. The payments made under ES may already overcome this barrier should positive GHG mitigation under ES be identified.
1.5. This project has provided an estimate of the GHG emissions (EDP), both on and off farm, associated with land under the various ES options (and C mitigation through changes in C sequestration) to provide an overall estimate of the net positive or negative change in CO$_2$ emissions. A robust, testable and cost-effective methodology to calculate the net CO$_2$e emissions of a given management practice on agricultural land requires development. This research has the potential to make an important contribution to developing such a methodology. It first defines a baseline set of conditions in order to provide a reference point against which any changes in land use through management under ES may be compared and the net increase or decrease in C equivalent emissions quantified. Since the aim of the project is to identify changes in CO$_2$e emissions, the quantification of stored C that does not change is not within scope. Reference has been made to the C storage potential of each habitat within ES and the importance of its continued maintenance or restoration even though the net change in emissions may be small. The overall impact on a national scale based upon the total area (ha) of uptake of each option within England as supplied by Natural England has then been quantified. The project does not aim to quantify the differences in the changes in C flow at a regional level based upon soil type, annual rainfall and through exact vegetation classification. Mean values have been used in many cases but they do allow comparisons between management scenarios and identify the main mechanisms of change associated with the management of each ES option.

1.1. Purpose from the research proposal

1.6. An assessment of the current contribution (both positive and negative) of Environmental Stewardship (ES) to climate change mitigation and consideration of potential new options for inclusion in Environmental Stewardship to increase the contribution to climate change mitigation.

1.2. Scientific Aims and Objectives from the research proposal

1. Review existing publications and data relevant to the major processes and changes in land use that contribute to greenhouse gas (GHG) emissions in UK agricultural systems
2. Application of processes outlined in (1) to changes in land use associated with individual options in each of the three Environmental Stewardship Schemes.
3. Recommendations for the preferred Environmental Stewardship options to mitigate GHG emissions (EDP) in UK agricultural systems and recommendations for other options to be included.
2.0 METHOD

2.1. Scope, boundary and baseline setting and management modifications under ELS, OELS and HLS options.

2.1. An initial scoping phase determined those options that were unlikely to contribute to changes in the net CO\textsubscript{2}e emissions, for example EB11 - Stone wall protection and maintenance. These options were not included in this study. A number of baseline agricultural production scenarios were constructed to provide a reference point against which any changes in land use or land management practices through the implementation of ES agreements could be compared and the net increase or decrease in the GWP quantified. The boundaries of each production scenario included all processes involved with the growing of the crop such as the manufacture and application of crop protection products (product, active ingredient and application rate per ha), and fertilisers (product, nutrient composition and application rate per ha), field operations (type of implement, depth of operation) and livestock (for grassland)\textsuperscript{18,19,20,21,22}. On farm transportation of the harvested crop to storage areas and post harvest operations such as grain drying were also included.

2.2. Winter wheat is the most widely grown crop within England, with 1,748,400 ha devoted to production in 2005, 39\% of the total land within cultivation\textsuperscript{23}. As one of the most widely studied crops within England with respect to its agronomy and environmental outputs\textsuperscript{18} it was set as a baseline for the arable system with which to compare each ES option (Appendix 1 Table 1.1). Where ES management specified alternative crops, for example spring sown crops, brassica crops or fodder crops then alternative baseline scenarios have been used (Appendix 1 Tables 1.2 – 1.4). A total of four baseline grassland scenarios of varying management intensity were also constructed. Firstly, intensively managed improved grassland either grazed by dairy cattle (Appendix 1 Table 1.5) or used for silage production (Appendix Table 1.6) (to supply winter feed for the livestock within the grassland scenarios). Secondly, less intensively managed semi-improved lowland or upland grassland grazed by either suckler cows or ewes at average stocking densities (Appendix 1 Table 1.7). Thirdly, unimproved grassland grazed by either suckler cows or ewes at low stocking densities (Appendix 1 Table 1.8). The OELS options were assigned an organically managed baseline that was constructed using the same method as described previously. A detailed description of the management regime for each baseline is given in Appendix 2 Tables 1.10 – 1.14 for ELS, HLS and OELS options respectively. The baseline assigned to each option and the changes relative to that baseline for the land when managed under ES are also given. A management scenario was then constructed for each ES option using the same method as described for the baseline scenario (summarised in Appendix 2). An inventory of the net CO\textsubscript{2}e emissions for management scenario of each option relative to the baseline was then calculated (section 2.2).

2.2. Inventory of greenhouse gas emissions: carbon dioxide, nitrous oxide and methane.

2.2.1. Emissions from the combustion of fossil fuels.

2.3. The GHG emissions that result from the combustion of fossil fuels during management of land under each ES option were quantified from the following three areas:

i. product manufacture (pesticides and fertilisers), packaging and transport (to farm) (Table 1)\textsuperscript{22,24,25,26,27}.

Table 1. The chemical composition of fertiliser products, the proportion of active ingredient in pesticides and the GHG emissions from their manufacture.

<table>
<thead>
<tr>
<th>Product</th>
<th>Composition</th>
<th>GWP (t CO\textsubscript{2}e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ammonium nitrate</td>
<td>34.5% N</td>
<td>0.00238 kg product\textsuperscript{14,25}</td>
</tr>
<tr>
<td>ammonium sulphate</td>
<td>21% N; 60% SO\textsubscript{3}</td>
<td>0.00034 kg product\textsuperscript{14,25}</td>
</tr>
<tr>
<td>triple superphosphate</td>
<td>45.5% P\textsubscript{2}O\textsubscript{5} (P\textsubscript{2}O\textsubscript{5} : 43.6% P)</td>
<td>0.00017 kg product\textsuperscript{14,25}</td>
</tr>
<tr>
<td>rock phosphate</td>
<td>28.5% P\textsubscript{2}O\textsubscript{5}</td>
<td>0.00097 kg P\textsuperscript{1,22}</td>
</tr>
<tr>
<td>muriate of potash</td>
<td>60% K\textsubscript{2}O (K\textsubscript{2}O : 83% K)</td>
<td>0.00020 kg product\textsuperscript{1,25}</td>
</tr>
<tr>
<td>sylvinite (rock K)</td>
<td>24% K\textsubscript{2}O</td>
<td>0.00086 kg K\textsuperscript{1,22}</td>
</tr>
<tr>
<td>lime (limestone)</td>
<td></td>
<td>0.00006 kg product\textsuperscript{1,22}</td>
</tr>
<tr>
<td>pesticides</td>
<td>20 gl\textsuperscript{1} – 80% w/w\textsuperscript{23}</td>
<td>0.000001 – 0.0296 per application</td>
</tr>
</tbody>
</table>

\textsuperscript{a}inclusive of N\(_2\)O released during manufacturing process.
The input of fossil fuels to overall energy (MJ kg$^{-1}$) required for the manufacture of herbicides, fungicides and insecticides are in the following proportions: 40% electricity (primary electricity), 22% natural gas, 5% fuel oil$^{22}$. The manufacture energy includes 23 MJ kg$^{-1}$ active ingredient for storage and transport. The GWP (kg CO$_2$ e per kWh ($3.6$ MJ) for fuel types: natural gas (0.19), diesel (0.25), fuel oil (0.26), naphtha (0.26) and coal (0.3)$^{22}$. 1 kWh of primary electricity requires 0.166 kg CO$_2$ e kWh$^{-1}$ but is not inclusive of energy losses during the conversion of fossil energy to electricity, the equivalent of 9.6 MJ per 3.6 MJ delivered to the meter. The CO$_2$ emissions have been calculated using the figure for primary electricity when the energy value has been taken from a life-cycle analysis of the product since this is inclusive of all energy consumed i.e. the primary fuels consumed during generation. Where electricity consumption is specified from a meter reading the delivered value of 0.430 kg CO$_2$ e kWh$^{-1}$ has been used.

ii. application by spraying or spreading or fuel consumed by tillage operations and drilling (direct energy) (Table 2)$^{22,27,29,30,31,32}$

iii. fuel consumed during machinery manufacture and calculated based on depreciation per operation (indirect energy) (Table 2)$^{22,25,26}$.

Table 2. The GHG emissions (t CO$_2$ e ha$^{-1}$) from direct and indirect sources (ranked from highest to lowest total per operation) $^{20,26,27,28,29}$.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Direct (t CO$_2$ e ha$^{-1}$)</th>
<th>Indirect (t CO$_2$ e ha$^{-1}$)</th>
<th>Total (t CO$_2$ e ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>subsoil (35 cm)</td>
<td>0.1119</td>
<td>0.0076</td>
<td>0.1195</td>
</tr>
<tr>
<td>plough (20 cm)</td>
<td>0.0820</td>
<td>0.0076</td>
<td>0.0896</td>
</tr>
<tr>
<td>spreading 30 t ha$^{-1}$ FYM</td>
<td>0.0457</td>
<td>0.0432</td>
<td>0.0889</td>
</tr>
<tr>
<td>power harrow</td>
<td>0.0485</td>
<td>0.0145</td>
<td>0.0630</td>
</tr>
<tr>
<td>chain harrow</td>
<td>0.0252</td>
<td>0.0038</td>
<td>0.0290</td>
</tr>
<tr>
<td>mole plough</td>
<td>0.0252</td>
<td>0.0038</td>
<td>0.0290</td>
</tr>
<tr>
<td>direct drill</td>
<td>0.0187</td>
<td>0.0069</td>
<td>0.0256</td>
</tr>
<tr>
<td>rolling (Cambridge rolls)</td>
<td>0.0192</td>
<td>0.0029</td>
<td>0.0221</td>
</tr>
<tr>
<td>stalk chopper</td>
<td>0.0192</td>
<td>0.0029</td>
<td>0.0221</td>
</tr>
<tr>
<td>baling</td>
<td>0.0158</td>
<td>0.0047</td>
<td>0.0205</td>
</tr>
<tr>
<td>spring tine harrows</td>
<td>0.0155</td>
<td>0.0040</td>
<td>0.0195</td>
</tr>
<tr>
<td>conventional drill</td>
<td>0.0143</td>
<td>0.0050</td>
<td>0.0193</td>
</tr>
<tr>
<td>spreading 125 kg ha$^{-1}$ mineral fertiliser</td>
<td>0.0053</td>
<td>0.0015</td>
<td>0.0068</td>
</tr>
<tr>
<td>pesticide application</td>
<td>0.0047</td>
<td>0.0015</td>
<td>0.0062</td>
</tr>
<tr>
<td>hedgerow cutter</td>
<td>0.00001 t$^{-1}$</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
<tr>
<td>*drying (winter wheat)</td>
<td>0.00301 t$^{-1}$</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
<tr>
<td>drying (spring barley)</td>
<td>0.00380 t$^{-1}$</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
<tr>
<td>drying (oilseed)</td>
<td>0.00460 t$^{-1}$</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

assumes $^{8}$85% and $^{8}$80% of the overall energy input is field diesel. The energy required for ploughing and subsoiling on various soil types have been derived from regression equations$^{21}$, harvest and mineral fertiliser spreading operations are based on weight$^{25}$, an additional 475.2 M J (0.033 t CO$_2$ e ha$^{-1}$) is required for transport assuming a mean on farm transportation distance of 2 km and fuel consumption of 0.2 t l$^{-1}$km$^{-1}$, 39.6 MJ t$^{-1}$ diesel$^{25}$, 88 tramlines per ha 2 m wide, 1600 m$^2$ ha$^{-1}$ or 0.16 ha. $^{*}$energy input for drying as 100% primary electricity, the indirect value is an estimate.

2.2.2. N$_2$O from soil

2.4. Data from the published literature on N$_2$O-N emissions from arable land are subject to variation and range, for example, between 0.7 – 2.4 kg N$_2$O-N ha$^{-1}$year$^{-1}$ $^{33}$, 1.4 – 3.7 kg N$_2$O-N ha$^{-1}$year$^{-1}$ $^{34}$, 3.0 – 24.0 (mean 11.8) kg N$_2$O-N ha$^{-1}$year$^{-1}$ $^{35}$ and 1.0 kg N$_2$O-N t$^{-1}$ winter wheat $^{24}$. The IPCC (2006) methodology $^{26}$ used default values for calculating N$_2$O emissions in the absence of national or regional data (Tier 1 approach) but recommended the use of national data where available (tier 2 or 3 approach). The Tier 1 approach has been subject to criticism for the overestimation of soil N$_2$O emissions when applied to UK arable conditions $^{37,38}$. An inventory of N$_2$O-N emissions from agricultural land by county within the UK reported that a range of between 0.99 – 3.75 kg N$_2$O-N ha$^{-1}$year$^{-1}$ was applicable to 69% of counties, the mainly arable areas within central and eastern England. For the current study the N$_2$O emissions from a winter wheat crop in receipt of standard fertiliser recommendations $^{39}$ have been calculated using the N balance model SUNDIAL $^{40}$ to simulate the quantity of N that is denitrified and nitrified under UK conditions. This allowed adjustments such as the non-application of fertiliser N to be made to the baseline conditions. The fraction of N$_2$O-N released from denitrification is estimated to range between 0.01 – 0.12 depending upon soil type $^{41}$ and a mean value of 0.035 has been assumed $^{17}$. The decomposition of plant biomass results in the formation of ammonium (NH$_4$$^+$).
Under aerobic conditions \( \text{NH}_4^+ \) oxidises to nitrite (\( \text{NO}_2^- \)) and ultimately nitrate (\( \text{NO}_3^- \)) via nitrification\(^{41} \). While \( \text{N}_2 \) exists as \( \text{NO}_3^- \) it may potentially form \( \text{N}_2\text{O} \), the fraction of which may vary between 0.005 – 0.02 and a mean factor of 0.0125 has been used\(^{41} \). SUNDIAL calculates the quantity of \( \text{N} \) that proceeds through the nitrification pathway, and the quantity of \( \text{N}_2\text{O} \) was estimated using a similar method to that described for denitrified \( \text{N} \). A third source of \( \text{N}_2\text{O} \) is from the volatilisation of ammonia (\( \text{NH}_3 \)) to which an emission factor of 0.01 kg\( \text{N}_2\text{O} \)-N kg\( \text{N} \) ha\(^{-1} \) volatilised\(^6 \) has been applied.

2.5. The \( \text{N} \) fertiliser regime, the soil type and the amount of rainfall may alter the quantity of \( \text{N} \) lost to denitrification\(^{19,42} \). For example, the overall \( \text{N}_2\text{O}-\text{N} \) emissions may be lower on a sandy soil during years of low rainfall compared to a clay soil during years of heavy rainfall. Nitrogen immobilisation, the reduction of soil inorganic \( \text{N} \) available for potential denitrification, occurs when the C:N ratio is above 25\(^{43} \). The incorporation of 3 t ha\(^{-1} \) of cereal straw is estimated to immobilise 20 kg\( \text{N} \) ha\(^{-1} \) \(^{44} \) as a result of an increased C:N ratio. The \( \text{N}_2\text{O} \) emission from sandy clay loam soil both with and without straw incorporation as simulated by SUNDIAL using the method described previously have been used in the current study for land under arable production. Sandy clay loam was simulated to avoid as far as possible extremes in outputs while the output was adjusted as 60% with straw and 40% without to reflect current UK agricultural practice. It is acknowledged that differences in geographical regions as a result of annual precipitation and variations in soil type in addition to management will impact on the emissions of \( \text{N}_2\text{O}-\text{N} \) from arable land and that significant variation exists. The impact of \( \text{N} \) fertiliser elimination from cereal headlands on the loss of \( \text{N} \) due to denitrification and associated \( \text{N}_2\text{O} \) losses has also been quantified with SUNDIAL using the method described previously (Table 3). For options such as fallow plots that are not in the same location each year this figure was also used. Where zero fertiliser was applied to land continually the emissions for unfertilised land were used in the calculations (Table 3) \(^{33,45} \). The \( \text{N}_2\text{O} \) losses that resulted from changes in land use from arable to, for example woodland, or grassland under ES options due to reduced fertiliser inputs were estimated from published literature\(^{12,13,14,34} \) (Table 3). Where legumes such as clover have been grown an additional 0.06 kg\( \text{N} \) ha\(^{-1} \) year\(^{-1} \) from N-fixation\(^6 \) has been added.

2.6. The \( \text{N}_2\text{O} \) emission factors on fertilised grassland were calculated from UK measurements\(^{33,45,46,47,48} \). Unfertilised grassland has been found to release 0.03 kg\( \text{N}_2\text{O} \)-N ha\(^{-1} \) year\(^{-1} \) \(^{33,48} \) and this figure has been used for options such as grass margins and unimproved grassland that receive little or no \( \text{N} \) (Table 3).

Table 3. The quantity of \( \text{N}_2\text{O} \)-N emitted from soil under different land uses and the net flow of \( \text{C} \) from \( \text{CH}_4 \) oxidation / emission within UK soils under different land uses and its \( \text{CO}_2 \) equivalent (negative value indicates removed from the atmosphere). The value for hedgerow was estimated as the mean of unfertilised grassland and woodland.

<table>
<thead>
<tr>
<th>Land use</th>
<th>( \text{N}_2\text{O}-\text{N} ) kg ha(^{-1} ) year(^{-1} )</th>
<th>( \text{t CO}_2\text{e} ) ha(^{-1} ) year(^{-1} )</th>
<th>( \text{CH}_4 ) kg ha(^{-1} ) year(^{-1} )</th>
<th>( \text{t CO}_2\text{e} ) ha(^{-1} ) year(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>*winter wheat</td>
<td>3.13 (2.69-3.75)(^{40} )</td>
<td>1.46</td>
<td>-0.650</td>
<td>-0.0156</td>
</tr>
<tr>
<td>*winter wheat no fertiliser N</td>
<td>1.47 (1.18-1.89)(^{40} )</td>
<td>0.68</td>
<td>-0.731</td>
<td>-0.0176</td>
</tr>
<tr>
<td>*organic rotation</td>
<td>1.69 (1.30-1.90)(^{40} )</td>
<td>0.77</td>
<td>-0.731</td>
<td>-0.0176</td>
</tr>
<tr>
<td>intensive grassland dairy cattle</td>
<td>2.14(^{33, 45, 47, 48} )</td>
<td>0.99</td>
<td>-0.650</td>
<td>-0.0156</td>
</tr>
<tr>
<td>semi-improved grassland</td>
<td>0.60(^{33, 45, 47, 48} )</td>
<td>0.28</td>
<td>-0.650</td>
<td>-0.0156</td>
</tr>
<tr>
<td>unfertilised grassland</td>
<td>0.30(^{40} )</td>
<td>0.14</td>
<td>-0.731</td>
<td>-0.0176</td>
</tr>
<tr>
<td>N-fixed by legumes (additional emissions)</td>
<td>0.06(^{40} )</td>
<td>0.027</td>
<td>-0.0156</td>
<td></td>
</tr>
<tr>
<td>woodland</td>
<td>1.50(^{36} )</td>
<td>0.69</td>
<td>-1.625</td>
<td>-0.0390</td>
</tr>
<tr>
<td>hedgerow</td>
<td>0.90</td>
<td>0.42</td>
<td>-0.731</td>
<td>-0.0176</td>
</tr>
<tr>
<td>drained peat (nutrient rich)</td>
<td>1.80(^{36} )</td>
<td>0.84</td>
<td>-22.265</td>
<td>0.5344(^{36} )</td>
</tr>
<tr>
<td>flooded land (cold, temperate, moist zone)</td>
<td>-</td>
<td>-</td>
<td>22.265</td>
<td>0.5344(^{36} )</td>
</tr>
</tbody>
</table>

\(^* \)The SUNDIAL simulations for the baseline ELS and HLS arable crops applied nitrogen fertiliser as ammonium nitrate and used MAFF (2000)\(^9 \) recommendations while for the organic crop the nitrogen supplied was simulated from the earlier ploughing of a grass ley with additional emissions from the \( \text{N} \) fixed by legumes summarised as follows:

i. sandy clay loam soil (SNS 1) 220 kg\( \text{N} \) ha\(^{-1} \) (split dressings of 40 kg\( \text{N} \) ha\(^{-1} \) early March, 90 kg\( \text{N} \) ha\(^{-1} \) late March, 90 kg\( \text{N} \) ha\(^{-1} \) mid-late April), soil depth of 150 cm, target yield 8.5 t ha\(^{-1} \).

ii. organic systems sandy clay loam soil grass ley ploughed in within the past 4 years with no additional \( \text{N} \).

The use of long term average weather data tends to eliminate extremes in the weekly rainfall inputs and risks under-estimation of de-nitrification if used in the simulations. Four weather data-sets from the Brooms Barn weather station with peaks in rainfall at different times of the season were simulated with a mean annual rainfall (± 1 standard error) of 647.4 mm
On grassland where fertiliser N is applied the N₂O emissions may vary in relation to the soil type and geographical location as discussed previously for arable soils. A spatial analysis to account for such differences was not within the scope of the current study. For the fertilised (with inorganic N) grassland scenarios the mean emission factor, the proportion of fertiliser N applied lost as N₂O-N, on sand (0.019) and clay (0.024) soils (MAFF, 2000 classification 29) have been used (Table 3). For options that specified a particular soil type such as sand dunes the emission factor was adjusted accordingly. The N₂O-N emissions from the application of slurry and FYM were calculated using the method outlined in the UK GHG Inventory 9 with the N adjusted for emissions that occurred during storage.

2.7. There is currently no specific guidance for the calculation of N₂O-N emissions from wetlands on mineral soils and emissions should be calculated as for agricultural run-off and waste water 36. The quantity of N that proceeds through the denitrification pathway is increased under anaerobic conditions that arise through the flooding of land 42. The emissions from unfertilised grassland (0.03 kgN₂O-N ha⁻¹ year⁻¹ 33,45) were assumed to be unchanged by flooding since no fertiliser N had been applied. Unfertilised drained nutrient rich peat soils (for example lowland fen) are estimated to lose 1.8 kgN₂O-N ha⁻¹ year⁻¹ 36. The emissions from unfertilised drained nutrient poor peat soils (such as upland rough grassland) were assumed to be the same as for unfertilised mineral soils, 0.03 kgN₂O-N ha⁻¹ year⁻¹ 33,45 (Table 3).

2.2.3. CH₄ from soil

2.8. Losses of CH₄ from arable systems and woodland are considered negligible 12,13,14,49,50. In aerobic soils CH₄ undergoes oxidation by methanotrophic soil bacteria with a net negative flow of C to the atmosphere. On land fertilised with mineral N this is calculated as 0.65 kgha⁻¹ year⁻¹ (0.0156 t CO₂e ha⁻¹ year⁻¹ removed) and estimated to increase by 25% on land not fertilised with mineral N (0.0176 t CO₂e ha⁻¹ year⁻¹)22 (Table 3). Fertilised arable land is estimated to oxidise 40% of the quantity of CH₄ of undisturbed woodland 46. In this study the 0.0156 t CO₂e ha⁻¹ year⁻¹ for fertilised arable land has been multiplied by 2.5 to estimate the rate of CH₄ oxidation in woodland. The CH₄ oxidation rate for hedgerow in the current study was estimated as the mean of unfertilised grassland and woodland.

2.9. Under anaerobic conditions CH₄ may be emitted from soil 59. This includes soils that typically act as a CH₄ sink under aerobic conditions, for example after heavy rainfall when the sub-surface soil becomes saturated and anaerobic conditions are present 51. The emission factor is influenced by the climatic zone which is in turn influenced by the mean annual temperature 36. The ES options that involve the flooding of land include the restoration of fen and lowland raised bog, habitats that are located within the Midlands, the East or the North of England. Within these geographical regions the mean annual temperature is below 10°C 52 thereby corresponding to classification as a cold, moist temperate zone with an emission factor of 22.3 kg CH₄ ha⁻¹ year⁻¹ (0.53 t CO₂e ha⁻¹ year⁻¹) 36.

2.2.4. CO₂ from soil

2.9. The emissions of CO₂ from soil have been calculated for high C containing organic (peat) soils (lowland raised bog and fen) that, upon decomposition under aerobic conditions following land drainage, release CO₂ 36. The emissions from drained lowland peat vary with peat depth, and a mean of 10.9 t CO₂e ha⁻¹ year⁻¹ is given for the UK 5. The baseline scenarios that contain drained peat soil were calculated to release 10.9 and 7.3 t CO₂ e ha⁻¹ year⁻¹ from lowland and upland peat soils respectively 5. Arable land on peat soils within the UK has been calculated to release 15.0 t CO₂ e ha⁻¹ year⁻¹ 36 and this figure was used for baselines that contained winter wheat grown on peat soil. Previous studies have suggested that the phenols responsible for the prevention of peat decomposition are destroyed when the soil is drained and that decomposition and thus loss of C as CO₂ continues for a period of time after restoration of the water table, the ‘enzyme-latch effect’ 53. The prevention of C loss by re-flooding peat soils may
therefore not be immediate. In the current study the CO\textsubscript{2} released from the soil after the re-flooding of the land was set at zero which is equivalent to a saving of for example 7.3 t CO\textsubscript{2}e ha\textsuperscript{-1}year\textsuperscript{-1} relative to the baseline on upland peat soils.

2.10. On arable land for all other soil types (classed as mineral soils under IPCC, 2006 guidelines\textsuperscript{36}) the soil C flux has been set at zero\textsuperscript{14} (at equilibrium). The potential net gains in SOC through changes in management are described in section 2.3. The release of CO\textsubscript{2} from soil also occurs as a result of the application of lime, calculated as 0.12 t C t\textsuperscript{-1} (0.44 t CO\textsubscript{2}e ha\textsuperscript{-1}year\textsuperscript{-1}) of limestone. This has been added to the emissions associated with the manufacture of the product (section 2.1).

2.2.5. Burning of residues

2.11. The contribution of CH\textsubscript{4} and N\textsubscript{2}O to the GHG emissions from the burning of heathland were 0.169 and 0.507 t CO\textsubscript{2}e ha\textsuperscript{-1}respectively\textsuperscript{36}.

2.2.6. Emissions from livestock

2.12. Methane emissions from the enteric fermentation of ruminant animals have been calculated using mean UK emission factors: 103.5, 48 and 8 kgCH\textsubscript{4} animal\textsuperscript{-1}year\textsuperscript{-1} from one cow (average dairy herd), one suckler cow and one breeding ewe respectively\textsuperscript{5}. The mean emission factors for CH\textsubscript{4} from livestock manures were 25.43, 2.74 and 0.19 kgCH\textsubscript{4} animal\textsuperscript{-1}year\textsuperscript{-1} respectively\textsuperscript{5}. It is acknowledged that the dietary composition impacts upon the CH\textsubscript{4} emission factors due to enteric fermentation and from manures for each livestock type and that the method of storage impacts upon the CH\textsubscript{4} emissions from livestock manures. The proportion of total manures stored by each method in the UK is accounted for in the mean values cited. For the purpose of scaling up the calculations of GHG emissions\textsubscript{(EDP)} per ha per option to the whole of England mean values were considered more appropriate. The N\textsubscript{2}O emissions from the handling and storage of livestock manures have been calculated for the given stocking rate, quantity of manures and N contained within that manure per individual livestock type per year (Table 4)\textsuperscript{5,49,54,55}. The composting of manure as a solid manure management strategy is undertaken in organic farms and a total emission factor (N\textsubscript{2}O and CH\textsubscript{4} combined and including handling) of 4.4 kg CO\textsubscript{2}e kgN\textsuperscript{-1} was used\textsuperscript{22}.

Table 4. The quantity of N\textsubscript{2}O-N and CH\textsubscript{4} released from livestock manures during a housed period or when deposited on pasture\textsuperscript{5}.

<table>
<thead>
<tr>
<th>Location &amp; type</th>
<th>Livestock</th>
<th>kg N\textsubscript{2}O-N kg N\textsuperscript{-1} excreted</th>
</tr>
</thead>
<tbody>
<tr>
<td>solid system</td>
<td>dairy cow</td>
<td>0.020</td>
</tr>
<tr>
<td>liquid system</td>
<td>dairy cow</td>
<td>0.001</td>
</tr>
<tr>
<td>solid system</td>
<td>other cattle (suckler cow)</td>
<td>0.020</td>
</tr>
<tr>
<td>solid system</td>
<td>ewe</td>
<td>0.020</td>
</tr>
<tr>
<td>grazing deposition</td>
<td>all</td>
<td>0.020</td>
</tr>
</tbody>
</table>

2.13. Dairy cattle were grazed for 175 days and housed for 190 days. Of the total 85.9 kg of N excreted 32.5 kgN (38%) was calculated as slurry and 7.2 kgN (8%) as FYM\textsuperscript{22}. The remainder 46.2 kgN (54%) was calculated as deposition on grass. On semi-improved grassland ewes were assumed housed for 30 days\textsuperscript{56} and suckler cows for 151 days (between 1\textsuperscript{st} November and 1\textsuperscript{st} April) per year\textsuperscript{22}. The emissions from manure storage were calculated as 100% FYM when indoors and as 100% deposition on grass during the outdoor period.

2.3. Carbon storage potential of land (sequestration)

2.3.1. Carbon storage potential of soil in England under different types of management

2.14. The mean SOC content to soil depths of 30 cm for four different land uses and inclusive of all soil types within England have been calculated\textsuperscript{36}. They are arable land (70 t C ha\textsuperscript{-1} or 256.7 t CO\textsubscript{2}e ha\textsuperscript{-1}), pasture (80 t C ha\textsuperscript{-1} or 293.3 t CO\textsubscript{2}e ha\textsuperscript{-1}), semi-natural habitat (120 t C ha\textsuperscript{-1} or 440.0
t CO₂ ha⁻¹) and woodland (100 t C ha⁻¹ or 366.7 t CO₂ ha⁻¹)⁵⁴. These SOC contents have been assumed for the respective land uses when at equilibrium. A baseline SOC of 256.7 t CO₂ ha⁻¹ for arable land that has not undergone management to improve SOC accumulation (section 2.3.2.) has been used for the ELS, HLS and OELS winter wheat, spring barley, winter oilseed rape and fodder rape scenarios.

2.15. For UK grasslands there is a distinction between grassland that is actively managed as pasture and semi-natural or natural grassland (semi-natural habitat)⁵⁸. Pasture includes improved managed grass where the improvement is usually by ploughing and seeding such as recently sown grass, pure rye, weedy swards and well managed grassland (Countryside Survey (CS) and Monitoring Landscape Change (MLC) classification)⁵⁹, ⁶⁰. The SOC content of intensive grassland depends largely upon the impact of ploughing and reseeding operations⁵⁷,⁵⁸. The intensive grassland grazed by dairy cattle scenario in the current study was assumed to be ploughing and reseeding every 8 years and has therefore been allocated a baseline SOC of 293.3 t CO₂ ha⁻¹ for the top 30 cm.

2.16. The MLC classification of semi-natural and unimproved grassland includes managed grass that is unimproved by ploughing and seeding (calcareous and upland), upland smooth and coarse grass, lowland rough grass and neglected grassland, marsh grass and moorland grass⁵⁵,⁵⁶. The scenarios of semi-improved and unimproved grassland grazed by suckler cows or ewes in the current study were not ploughed or re-seeded. They were grouped with the semi-natural or natural habitat and allocated a baseline SOC of 120 t C ha⁻¹ (440.0 t CO₂ ha⁻¹) for the top 30 cm⁵⁸. The semi-natural or natural habitats also include heathland and blanket bog consequently the SOC content is not specific to grassland alone. The SOC of the other baseline semi-natural or natural habitats in the current study with the exception of woodland, sand and peat soil have been given a SOC at equilibrium of 120 t C ha⁻¹ (440.0 t CO₂ ha⁻¹). The SOC allocated to woodland was 100 t C ha⁻¹ (366.7 t CO₂ ha⁻¹)⁵⁸. The options that were implemented specifically on sand soil (for example the creation of sand dunes) were assumed not to increase in the SOC any further relative to the existing baseline.

2.17. The SOC content is also dependent upon the soil type (namely percent clay content) where two distinct groups have been identified: coarse loamy and sandy soils (with less than 18% clay); and fine loamy and clayey soils (with 18% or more clay)⁶¹. The annual precipitation which, as discussed for N₂O emissions from soil is influenced by geographic location is also a factor. The inclusion of such spatial factors within the analysis was beyond the boundaries of the current study.

2.3.2. Changes in SOC

2.18. Changes in SOC may occur in two ways. The first, and most significant route is through a permanent change in land use where the SOC establishes a new content when it is at equilibrium relative to that of the original land use⁵⁸,⁶². The new equilibrium is established when the oxidation of SOC equals the C accumulated from increased organic matter returns¹⁵. The second route is though permanent changes to management that maintain the land use within the same classification but shift the SOC content at equilibrium. This is predominantly within arable land¹²,¹³,¹⁵. The C savings (EDP) from, for example, reduced fuel consumption during any one year (section 2.2) are permanent. In contrast any gain in the C sequestered within the soil as a consequence of management that results in an increase in C accumulation is vulnerable to loss should the original management regime be re-instated⁵,¹⁵,³⁶,⁶²,⁶⁵,⁶⁶. This loss has been found to be at an exponential rate and the C sequestered will be lost and returned to its original equilibrium more rapidly than it was gained⁶⁷. The calculated reduction in net GHG emissions (EDP) as a result of ES therefore depends upon the continued management within the agreement.

2.19. The majority of disturbance and change to the SOC of arable land occurs to a depth of 30 cm¹²,¹³,¹⁴,⁴⁶,⁶⁶,⁶⁹,⁷⁰. Changes to the SOC of arable land that remains under arable management were calculated to the 30cm depth in this study. The percentage change in SOC per year to a depth of 30 cm associated with various arable land management practices has been calculated using regression equations¹²,¹³ or from published literature¹⁵ (Table 5).
Table 5. The rate of soil and above ground C accumulation (t CO₂e ha⁻¹·year⁻¹), the maximum quantity at equilibrium (t CO₂e ha⁻¹·year⁻¹) and the estimated number of years to reach that equilibrium assuming continuous management under that regime for land managed within ES. Where a change in land use has occurred the change in AGC is applicable to that year only (the year the change occurs). For the following years any change is described by management within the same land use between years and the number of years to reach the maximum stated (the C accumulation is zero for any year that is not given). Where a baseline habitat consists of multiple vegetation structures the SOC and AGC of the individual habitats have been multiplied by the proportion in which they are present.

<table>
<thead>
<tr>
<th>Land use</th>
<th>SOC acc rate ( R_{SOC} )</th>
<th>Max SOC to 30cm</th>
<th>Year(s) after change</th>
<th>AGC acc rate ( R_{AGC} )</th>
<th>Max AGC</th>
<th>Year(s) after change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>on arable land</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minimum tillage</td>
<td>0.15</td>
<td>275.0</td>
<td>1 - 100</td>
<td>0</td>
<td>8.07</td>
<td>1 - 100</td>
</tr>
<tr>
<td>zero tillage</td>
<td>0.7</td>
<td>275.0</td>
<td>1 - 26</td>
<td>0</td>
<td>8.07</td>
<td>1 - 100</td>
</tr>
<tr>
<td>agricultural extensification (grass ley)</td>
<td>2.62</td>
<td>275.0</td>
<td>1 - 7</td>
<td>0</td>
<td>8.07</td>
<td>1 - 100</td>
</tr>
<tr>
<td>(1.02%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>arable to bare soil only</td>
<td>0</td>
<td>256.7</td>
<td>1</td>
<td>-8.07</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>arable to bare soil &amp; natural regeneration (annual tillage)</td>
<td>0</td>
<td>256.7</td>
<td>1</td>
<td>-4.40</td>
<td>3.67</td>
<td>1</td>
</tr>
<tr>
<td>natural regeneration to natural regeneration (annual tillage)</td>
<td>1.66</td>
<td>440.0</td>
<td>1</td>
<td>-4.40</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>arable to bare soil &amp; one year natural regeneration (mown)</td>
<td>(0.65%)</td>
<td>440.0</td>
<td>1</td>
<td>-4.40</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>natural regeneration year one to natural regeneration year two (mown)</td>
<td>3.32</td>
<td>440.0</td>
<td>2</td>
<td>3.67</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>natural regeneration year two to natural regeneration year three (max AGC) (mown)</td>
<td>(1.30%)</td>
<td>440.0</td>
<td>3</td>
<td>1.47</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>natural regeneration to natural regeneration (mown)</td>
<td>3.32</td>
<td>440.0</td>
<td>4</td>
<td>0</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>arable to sown grass strips (mown)</td>
<td>(1.30%)</td>
<td>440.0</td>
<td>1</td>
<td>0.73</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>arable reversion to semi-improved grassland</td>
<td>3.32</td>
<td>440.0</td>
<td>1</td>
<td>0.73</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>arable to lowland heathland (Calluna)</td>
<td>(1.57%)</td>
<td>440.0</td>
<td>1</td>
<td>-7.45</td>
<td>6.2*</td>
<td>1</td>
</tr>
<tr>
<td>lowland heathland (Calluna) to lowland heathland</td>
<td>3.32</td>
<td>440.0</td>
<td>2 - 55</td>
<td>0.62</td>
<td>6.2*</td>
<td>2 - 10</td>
</tr>
<tr>
<td>lowland heathland (Calluna) to lowland heathland</td>
<td>(1.30%)</td>
<td>0</td>
<td>56 - 100</td>
<td>0</td>
<td>6.2*</td>
<td>11 - 100</td>
</tr>
<tr>
<td>arable to woodland</td>
<td>3.00</td>
<td>366.7</td>
<td>1</td>
<td>2.20</td>
<td>513.3</td>
<td>1</td>
</tr>
<tr>
<td>arable to woodland</td>
<td>(1.17%)</td>
<td>366.7</td>
<td>2 - 37</td>
<td>10.27</td>
<td>513.3</td>
<td>2 - 50</td>
</tr>
<tr>
<td>arable to woodland</td>
<td>0</td>
<td>366.7</td>
<td>38 - 100</td>
<td>0</td>
<td>513.3</td>
<td>51 - 100</td>
</tr>
<tr>
<td><strong>on improved grassland</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>improved grassland to unimproved grassland</td>
<td>4.03</td>
<td>440.0</td>
<td>1</td>
<td>2.93</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>improved grassland to unimproved grassland</td>
<td>(1.30%)</td>
<td>440.0</td>
<td>2 - 39</td>
<td>0</td>
<td>8.8</td>
<td>2 - 100</td>
</tr>
<tr>
<td>improved grassland to semi-improved grassland</td>
<td>4.61</td>
<td>440.0</td>
<td>1</td>
<td>2.93</td>
<td>8.8</td>
<td>1</td>
</tr>
<tr>
<td>improved grassland to semi-improved grassland</td>
<td>(1.57%)</td>
<td>440.0</td>
<td>2 - 32</td>
<td>0</td>
<td>8.8</td>
<td>2 - 100</td>
</tr>
<tr>
<td>improved grassland to woodland</td>
<td>3.43</td>
<td>440.0</td>
<td>1</td>
<td>4.40</td>
<td>513.3</td>
<td>1</td>
</tr>
<tr>
<td>improved grassland to woodland</td>
<td>(1.17%)</td>
<td>440.0</td>
<td>2 - 21</td>
<td>10.27</td>
<td>513.3</td>
<td>2 - 50</td>
</tr>
<tr>
<td>improved grassland to pollen &amp; nectar mix</td>
<td>-3.67</td>
<td>275.0</td>
<td>1</td>
<td>2.20</td>
<td>8.07</td>
<td>1</td>
</tr>
<tr>
<td>improved grassland to pollen &amp; nectar mix</td>
<td>(1.17%)</td>
<td>275.0</td>
<td>2 - 5</td>
<td>0</td>
<td>8.07</td>
<td>2 - 100</td>
</tr>
<tr>
<td>grass strips / unimproved grassland to woodland</td>
<td>0</td>
<td>440.0</td>
<td>10.27</td>
<td>513.3</td>
<td>1 - 50</td>
<td></td>
</tr>
</tbody>
</table>

*AGC at maturity 12.4 t CO₂e ha⁻¹ after 10 years (10% burnt per year over a 10 year rotation maximum AGC 6.2 t CO₂e ha⁻¹ during any one year).

bSOC accumulation during year 1 (establishment of ground cover proceeded by mowing) 50% grass field margins.

AGC 3.67 t CO₂e ha⁻¹·year⁻¹ (subtract 8.07 t CO₂e ha⁻¹ as loss from baseline year 1) to maximum of 8.8 t CO₂e ha⁻¹.

SOC decreased from 293.3 to 275.0 t CO₂e ha⁻¹ after 5 years.

The AGC for the organic arable scenario was adjusted to 47% of that of arable crops based on the ratio to yields for winter wheat. The SOC content was assumed to be 275.0 t CO₂e ha⁻¹ when at equilibrium.

The period required for the establishment of a new SOC content at equilibrium is again uncertain and highly variable with estimates ranging from six years to up to 20 years after a change in cultivation regime and several decades after treatment with FYM15. The use of grass/clover leys within extensive rotations has been found to increase the SOC content.
relative to non-extensive rotations although the magnitude of this increase has been found to be variable\cite{12,13,15}. Organically managed cultivated land has been reported to contain 0.92% C after 10 years compared to 0.79% C on conventionally managed farmland on account of a greater return of organic matter\cite{74}. The maximum SOC at equilibrium attainable for the top 30 cm of cultivated land in England was set at 75 t C ha\(^{-1}\) (275.0 t CO\(_2\)e ha\(^{-1}\)) based upon the mean SOC of cultivated (annual tillage regime) and intensively managed grassland (ploughed and re-seeded every 8 years). An increased return of organic matter to the soil from for example cereal straw is between 1.95 and 2.63 t CO\(_2\)e ha\(^{-1}\)year\(^{-1}\) \cite{17}. A reduction in the frequency of tillage from the inclusion of a grass / clover ley for two years in a six year rotation (agricultural extensification) has been calculated as 2.62 t CO\(_2\)e ha\(^{-1}\)year\(^{-1}\) \cite{12,13,14}. This was assumed for all OELS options on cultivated land.

2.20. The baseline scenarios were assumed to be at equilibrium (the annual change in the SOC was zero). The rate of change in the SOC\cite{12,13,14} of arable land that was converted to another land use such as grassland or woodland and the new SOC content at equilibrium\cite{58} are described in Table 5. The magnitude of change and the time over which the change occurs to reach equilibrium are currently uncertain with estimates of 10 years\cite{15} to several decades\cite{14,17}. The change in the SOC of each land use was calculated by allocating a SOC content at equilibrium within one of the four categories of land management (arable, pasture, semi-natural or woodland) listed previously\cite{54}, then subtracting the SOC content of the previous (baseline) land use from the new land use. The time taken to establish the new equilibrium was calculated using the C accumulation rates\cite{12,13,14} given in Table 5 and is summarised in equation 1.

\begin{equation}
T = (SOCe_{eqb(option)} - SOCe_{eqb(baseline)}) / R_{(SOC)} \\
T = \text{Time to establish new SOC equilibrium} \\
SOCe_{eqb(option)} = \text{SOC at equilibrium (t CO}_2\text{e ha}^{-1}\text{)} of the option (new land use) \\
SOCe_{eqb(baseline)} = \text{SOC at equilibrium (t CO}_2\text{e ha}^{-1}\text{)} of the baseline scenario (current land use) \\
R_{(SOC)} = \text{SOC accumulation rate (t CO}_2\text{e ha}^{-1}\text{ year}^{-1}\text{)} for a given change in land management (Table 5)
\end{equation}

It is acknowledged that within the same land use variations in soil type will result in differences in the maximum potential SOC at equilibrium. In grassland where there is no change in either the type or the intensity of management the equilibrium does not change\cite{36}. This was also applicable to the intertidal and coastal options such as the creation of sand dunes where the SOC is unlikely to increase as a result of a management change. A change in the current land use from improved (ploughed and re-seeded) to semi-improved or unimproved grassland (without ploughing and reseeding) was calculated to increase the rate of SOC accumulation as described in Table 5 to a new SOC content of 440.0 t CO\(_2\)e ha\(^{-1}\) at equilibrium. The rate of SOC accumulation in grassland is influenced by improvements such as fertiliser, liming and mixed swards that contain N-fixing legumes\cite{61,72,73}. Any management improvement that results in an increased rate of growth also results in an increased rate of SOC accumulation\cite{36}. The SOC accumulation rate for the conversion of intensive grassland to semi-improved grassland was calculated as 1.57%\cite{12} on account of improvements from fertiliser N and lime. This was also applicable to the organic semi-improved grassland scenario that applied lime and spread grazing deposition with a chain harrow. The rate of SOC accumulation for conversion to unimproved grassland was calculated as 1.30%\cite{14} since no soil improvements were made. The change in SOC for land converted from semi-improved or unimproved grassland to woodland was zero\cite{55}.

2.21. The C contained within soil may be lost as particulate organic carbon (POC) or dissolved organic carbon (DOC) when soil is subject to water erosion\cite{74}. The quantity of soil and thus C removed as a result of water erosion is subject to a number of variables that are illustrated by the Universal Soil Loss Equation (USLE)\cite{75} and the Revised Universal Soil Loss Equation (RUSLE)\cite{76}. The quantity of soil and hence the C contained within it that is removed from the area of land under assessment is dependent upon the quantity of rainfall (and thus geographic location), the soil type and the topography of the land. The erosivity of rainfall refers to the energy contained within each droplet and this tends to be greater during summer storms. The impact of management within an individual field on soil loss includes the percentage area of soil that is exposed, the period and time of year. The height (m) that raindrops fall from the crop canopy, the time elapsed since the last tillage operation and the presence of organic material such as FYM are also major contributing factors\cite{75,76}. The quantity of soil loss, and
thus C loss, is therefore highly site specific. The impact of such losses on GHG emissions is also likely to be site specific since the contribution to GHG emissions of the C lost depends upon its fate after its removal. If the C is in the form of POC and DOC in water and consequently within an anaerobic environment the formation of CO$_2$ is unlikely (section 2.2.4). The run-off will either enter a water course where the DOC will remain within an anaerobic environment or be deposited on ground of a low gradient when the water flow is reduced sufficiently. For the latter case the C will be exposed to oxidation and thus loss as CO$_2$. The implications of soil erosion on GHG emissions were not calculated due to the highly site specific nature of loss and the uncertainty of the fate of the C. The potential for an option to increase or prevent soil erosion was highlighted where relevant.

### 2.3.3. Carbon storage potential above ground

2.22. The AGC storage potential of a habitat is dependent upon the quantity of biomass, 50% of which is estimated to be C\textsuperscript{33}. It refers to standing biomass and is applicable to the entire plant inclusive of the roots\textsuperscript{14}. Heavily grazed grassland may store 1.6 t C ha\textsuperscript{-1} (5.9 t CO$_2$e ha\textsuperscript{-1}) in total due to the short sward height that results from the continual removal by livestock. Less intensively grazed grassland may store up to 2.4 t C ha\textsuperscript{-1} (8.8 t CO$_2$e ha\textsuperscript{-1}) while, for a habitat such as woodland that contains a greater quantity of above ground biomass, the storage potential may be 140 t C ha\textsuperscript{-1} (513 t CO$_2$e ha\textsuperscript{-1}) (Table 5)\textsuperscript{12,13,14}.

2.3.4. Changes in above ground carbon

2.23. Different habitats will reach their full biomass potential over different periods of time. For arable crops and grassland it is within one year, consequently any change in the AGC that results from the conversion to such a habitat will occur in the first year only\textsuperscript{12,13,14}. For habitats that reach their AGC equilibrium after one year the change in the AGC is calculated as the AGC of the new habitat minus the total AGC of the previous habitat. If there is no change in the type of land management the net gain in AGC is zero after year 1. Habitats such as semi-natural woodland require several years to reach their full AGC sequestration potential (a mean of 50 years has been assumed to reach \textsuperscript{12,13,14}). The yearly AGC accumulation has been calculated as the maximum AGC sequestration potential divided by the time taken to reach that maximum. This assumes a constant yearly rate of accumulation (10.27 t CO$_2$e ha\textsuperscript{-1} year\textsuperscript{-1} (Table 5)) although it is acknowledged that this may be subject to variation depending upon the age of the tree and the species. Management interventions such as mowing or scrub or tree removal result in the loss of most AGC within the habitat within a short time frame (one year). The re-accumulation of this C may be more gradual over a number of years. The change in AGC during the first year after a change in management regime where such management interventions may have been used tends to be different to subsequent years. It was calculated as the yearly AGC accumulation rate of the new habitat (Table 5) minus the total AGC content of the previous habitat. This may result in an initial loss of AGC where the previous habitat contained a greater quantity of AGC than would be accumulated within the first year by the new habitat. The changes in AGC associated with conversion between two different habitats\textsuperscript{5, 12,13,14,36} are given in Table 5. The yearly AGC accumulation rate of the new habitat only (Table 5) was then added during each of the following years until the new equilibrium was reached.

### 2.4. Impact assessment

2.24. A GHG balance\textsubscript{(EDP)} for each baseline scenario and those ES options not eliminated during the scoping phase has been calculated using t CO$_2$e ha\textsuperscript{-1}year\textsuperscript{-1} to standardise the emissions\textsuperscript{36,77} derived in section 2.2 minus the C sequestered relative to the specified baseline conditions for each option defined in section 2.3 (Equation 2).
Equation 2.
\[
\text{GHGbalance}_{(EDP)} = (m + d + i + Ns + Gs + Cs + Nl + Gf + Gl) - (\text{Seq}_{(SOC)} + \text{Seq}_{(AGC)})
\]

Where:
- \( \text{GHGbalance}_{(EDP)} = \) GHG balance, excluding displaced production, during year \( n \) (t CO\(_2\)e ha\(^{-1}\) year\(^{-1}\))
- \( m = \) emissions from the manufacture of agro-chemicals (fertilisers, pesticides)
- \( d = \) direct emissions from the operation of machinery (application of agro-chemicals, tillage operations, harvest, drying)
- \( i = \) indirect emissions associated with the manufacture of machinery taking account of machinery depreciation
- \( Ns = \) emission of N\(_2\)O from soils
- \( Gs = \) emission of CH\(_4\) from soils
- \( Cs = \) emission of CO\(_2\) from soil
- \( Nl = \) emission of N\(_2\)O from manures
- \( Gf = \) emission of CH\(_4\) from enteric fermentation
- \( Gl = \) emission of CH\(_4\) from manures
- \( \text{Seq}_{(SOC)} = \) C sequestered in soil during year \( n \)
- \( \text{Seq}_{(AGC)} = \) C sequestered in plant biomass during year \( n \)

The total CO\(_2\)e emissions (t CO\(_2\)e ha\(^{-1}\) year\(^{-1}\)) and the net direction (positive or negative) to the atmosphere for each ES option evaluated relative to the baseline set of conditions for a given year (years 1 to 100) has then been calculated (Equation 4).

Equation 4.
\[
d\text{GHG flux} = \text{GHGbalance}_{(EDP)\text{option}(n)} - \text{GHGbalance}_{(EDP)\text{baseline}}
\]

where
- \( d\text{GHG flux} = \) change in net GHG balance\(_{(EDP)}\) during year \( n \) (years 1 to 100)
- \( \text{GHGbalance}_{(EDP)\text{option}(n)} = \) net GHG balance\(_{(EDP)}\) of the option during year \( n \) (years 1 to 100)
- \( \text{GHGbalance}_{(EDP)\text{baseline}} = \) net GHG balance of the baseline scenario (winter wheat, improved, grazed grassland, unimproved grassland or semi-natural grassland depending on the option)

The net change relative to the baseline (t CO\(_2\)e ha\(^{-1}\) year\(^{-1}\)) is equal to the CO\(_2\)e of the ES scenario minus the annual gain in SOC and AGC for the specified year as a result of the management change minus the GHG emissions from the original baseline scenario.

2.25. The management requirements for each option changed mostly during years 1 and 2, the changes in the AGC generally altered after periods of 1, 5 or 50 years and the change in SOC up to 55 years (Table 5). Five periods of cumulative net CO\(_2\)e emissions were simulated (1, 5, 25, 50 and 100) to account for these changes. The calculated SOC over the periods analysed (1 – 100 years) assumed that the new land use / management conditions had been continued uninterrupted without reversion to the previous baseline management regime during these periods. If at the end of these periods the original tillage and management regime was reinstated then it is likely that the SOC would be returned to its original level at equilibrium.

2.26. Most options are specified in the management protocols on a per ha basis. For options that are specified on areas of less than 1 ha (such as skylark plots) the area as a fraction of 1 ha has been multiplied by the total C mitigation\(_{(EDP)}\) potential to give the CO\(_2\)e savings\(_{(EDP)}\) per unit of option. For options such as hedge margins and ditches that are specified as per 100 m length the area per unit has been calculated as the length (100 m) multiplied by the margin width expressed as a fraction of 1 ha.

2.5. Area under each option

2.27. The uptake of each ELS, OELS and HLS option were provided by Natural England and multiplied by the net CO\(_2\)e emissions per unit of option for the five time periods described in section 2.4. Further uptake data and the ES scheme equivalent option for the Countryside Stewardship Schemes (CSS) and Environmentally Sensitive Areas (ESA) have also been provided. The current impact of those options relative to the QELRC between 2008 and 2012 on a national scale was then calculated. This method assumes that existing C stores within ES
remain as C stores and loss, as calculated by the C balance for maintenance options, does not occur.
3.0. RESULTS

3.1. Baseline production scenarios

3.1.1. The main contributors to the GHG emissions, EDP, from each baseline scenario are summarised in Figure 1. A detailed description of each baseline scenario is given in Appendix 1. Previous studies have analysed the energy consumption and GHG emissions of arable crop production and grassland in detail. The arable baseline scenarios in concurrence with previous studies were dominated by GHG emissions associated with the use of N fertiliser, soil conditioners such as lime, the emission of N\textsubscript{2}O from soil and deeper tillage operations such as ploughing. Smaller GHG emissions resulted from individual pesticide applications, shallow cultivations, harvest and post harvest operations were grouped together. The GHG emissions from the baseline scenarios that included livestock, the intensive grassland grazed by dairy cattle in particular, were dominated by enteric fermentation, the production of feed and emissions from manures. The baseline scenarios that included drained peat also released CO\textsubscript{2} from the soil. The organic arable baseline scenarios did not use inorganic fertiliser or pesticides but did apply lime. A three year grazed grass / clover ley and a single year of clover supplied the crop nutrients. The emissions associated with the maintenance of the ley and red clover were divided among four cash crops and three years livestock production. Farmyard manure and slurry were applied solely to grassland cut for silage. The lower yield of organic crops (4.0 t ha\textsuperscript{-1} compared to 8.5 t ha\textsuperscript{-1} for conventional winter wheat\textsuperscript{54,55}) resulted in the mean AGC of the organic arable scenarios reduced to 47% of the conventional arable scenarios. Emissions from enteric fermentation and the production of feed dominated the grassland baselines. The application rates of N fertiliser to the conventional grassland baseline scenarios were lower than the arable baseline scenarios. The GHG emissions from most other baseline scenarios (semi-natural habitat) were largely N\textsubscript{2}O from soil and emissions from livestock where grazed.

![Figure 1. The GHG emissions (t CO\textsubscript{2}e ha\textsuperscript{-1} year\textsuperscript{-1}) for each baseline scenario at equilibrium (no further accumulation of SOC or AGC).](image-url)

3.2. A more detailed breakdown of the GHG emissions derived from the inputs (crop nutrition, pesticides, field operations, post harvest, livestock feed) applied to selected (arable and grassland) baseline scenarios are shown in Figure 2. The total GHG emissions from N fertiliser is composed of N\textsubscript{2}O released during the manufacture of nitric acid in addition to the energy required from the combustion of fossil fuels. The manufacture of lime while not an energy intensive process in itself (extraction from the ground) releases CO\textsubscript{2} after its application.\textsuperscript{5
3.2. Climate change mitigation (EDP) per unit of option per year

3.3. The impact on the GHG emissions (EDP) and the CO₂e savings (EDP) as a result of alterations to the land management regime under ES (summarised for each option in Appendix 2) in comparison to the original baseline scenario after five years and the main causal factors are discussed for the ELS, HLS and OELS. Where longer-term changes have been forecast after 50 or 100 years reference has been made. The options displayed graphically in Figures 3 – 6 have been selected as representative of a group of options with similar GHG mitigating properties. A full list of options and the total and mean reduction in GHG emissions (EDP) ranked by the highest to lowest reduction per year calculated after five years is given in Appendix 3. The five year period was chosen for the focus of discussion in order to account for the differences in management that occurred during the first and second years for many options and to give an indication of the current status of GHG mitigation (EDP) from the implementation of ES. The initial commitment period under the Kyoto Protocol in which emissions are compared to 1990 levels is also for five years (2008–2012).

3.2.1. ELS options

3.4. The mean net GHG emissions (EDP) per ha for land managed under each ELS option after five years, the original GHG emissions from the baseline scenario and the net change (t CO₂e ha⁻¹ year⁻¹) are shown in Figure 3.
Figure 3 highlights the difference in the GHG emissions of the four baseline scenarios used and the potential for any reduction through alteration the management to that prescribed in the ELS options. The first grouping represents options implemented on arable land of which the maintenance of woodland edges (option EC4), virtually input free grass strips (EE1 – EE3) or habitat under similar management (EF1 field corner management or EF7 beetle banks) offered the greatest potential to reduce both emissions and increase the C accumulated and stored within the land. A breakdown of reductions by source is displayed graphically in Figure 4. The non-cultivation of the land potentially allows the SOC to reach an equilibrium at 440.0 t CO$_2$ e ha$^{-1}$. Options that created a buffer zone adjacent to hedgerows (for example option EB8 (hedgerow management on both sides of hedge)) were similar except natural regeneration was calculated to occur on 75% of the 2m margin. On the remaining 25% it was assumed that mature (post year 5) hedgerow already existed where there was no further change. The next grouping of options on land removed from cultivation reverted land from an arable rotation to semi-improved grassland (no ploughing or re-seeding) an example of which is option ED2 (take archaeological features currently on cultivated land out of cultivation). The net decrease (mean -4.73 t CO$_2$ e ha$^{-1}$ year$^{-1}$ after five years) could largely be attributed to the potential of the non-cultivation of land to establish a greater SOC content at equilibrium as described previously. The accumulation of SOC ceased post year 55 whereupon there were net CO$_2$ e emissions to the atmosphere. The reduction in the permanent emissions from the manufacture and application of pesticides and fertilisers from a shift from a winter wheat to a semi-improved grassland management scenario was attributed to a greater increase in emissions associated with the introduction of livestock at semi-improved grassland stocking rates (Figures 1 and 4). It is important to note that this calculation was solely for comparison with winter wheat. For other crops on cultivated land that may have greater GHG emissions during their production there would be a net CO$_2$ e saving.
Figure 4. The mean change per year in GHG emissions\(_{\text{(EDP)}}\) (t CO\(_2\)e ha\(^{-1}\)) after five years for each emission source or C sequestration type relative to the original baseline scenario (grouped by winter wheat, intensive grassland grazed by dairy cattle, semi-improved grassland and unimproved grassland), for selected ELS, HLS options mentioned previously that also had potential to establish an equilibrium with a greater SOC content.

3.5. Where the land was maintained within cultivation the potential to increase the SOC at equilibrium was greatly reduced from 440.0 to 275.0 t CO\(_2\)e ha\(^{-1}\). Options included within this grouping such as the pollen and nectar mixture (option EF4) were assumed to be re-established (the land cultivated and re-sown with the incorporation of the AGC) every two years. The assumed biennial tillage regime and the similarity in the quantity of AGC incorporated to grass (up to 8.8 t CO\(_2\)e ha\(^{-1}\)) was comparable to the inclusion of a grass clover ley within the rotation. The maintenance of the land within cultivation but at a reduced tillage frequency allowed the establishment of the SOC at equilibrium at 275.0 t CO\(_2\)e ha\(^{-1}\) at a rate of 2.62 t CO\(_2\)e ha\(^{-1}\). A permanent reduction in the GHG emissions\(_{\text{(EDP)}}\) resulted from no application of fertilisers and a reduction in tillage operations and pesticide use. A similar mechanism was applicable to the wild bird seed mixture (option EF2) except inorganic fertiliser applications were adjusted to those of fodder rape (Appendix Table 1.4). The undersowing of a spring cereal with a grass / clover mixture (option EG1) offered potential to substitute up to 200 kgNha\(^{-1}\) applied originally as ammonium nitrate\(^{39}\). The rate of increase of the accumulation of SOC (an estimated 2.62 t CO\(_2\)e ha\(^{-1}\)year\(^{-1}\) for a two year ley present every six years\(^{12,13}\)) is dependent upon its duration. In option EG1 the ley remained in place for a minimum of one year as opposed to two consequently the accumulation of SOC was estimated as 50% of that of a two year ley (1.31 t CO\(_2\)e ha\(^{-1}\)year\(^{-1}\)). The longer term C mitigation\(_{\text{(EDP)}}\) properties of these options tended to decrease after between seven and 14 years relative to the options on land removed from cultivation that had potential to establish a SOC content at equilibrium of 440.0 t CO\(_2\)e ha\(^{-1}\) after 55 years. After this time all CO\(_2\)e savings\(_{\text{(EDP)}}\) were permanent the same as cultivated land that did not alter the frequency of tillage. An exception was option ED3 (reduce cultivation depth on archaeological features) where an arable rotation remained but the soil was minimum tilled a consequence of which was a reduction in diesel use and an annual increase in the SOC accumulation of 0.15 t CO\(_2\)e ha\(^{-1}\). The impact of minimum tillage upon N\(_2\)O emissions however requires further quantification, current estimates have been used\(^{15}\). The smaller rate of SOC accumulation resulted in an established equilibrium of 275.0 t CO\(_2\)e ha\(^{-1}\) after an estimated 125 years thus the net reduction in GHG emissions\(_{\text{(EDP)}}\) was lower than the options mentioned previously that also had potential to establish an equilibrium with a greater SOC content.
3.6. On cultivated land that did not alter the frequency of tillage the SOC at equilibrium remained constant and the reduction in the GHG emissions (EDP) were permanent. The selective application of herbicide by weed wiper allowed the natural regeneration of AGC in option EF11 (6 m uncropped, cultivated margins on arable land) however the establishment of vegetation by such means was not as rapid as from the sowing and cultivation of a crop. A loss of AGC of 4.40 t CO$_2$ e ha$^{-1}$ relative to the winter wheat baseline resulted during year one only while annual tillage prevented further accumulation (Figures 3 and 4). The main CO$_2$ e saving from option EF 10 (conservation headlands in cereal fields with no fertilisers or manures) and option EG5 (brassica fodder crops followed by over-wintered stubbles) arose from the elimination of or the reduction in the application of N and the soil N$_2$O emissions. A reduction in the GHG emissions of less than 1.0 t CO$_2$ e ha$^{-1}$ year$^{-1}$ occurred in those options that reduced inputs such as pesticides or light field operations. The options with the smallest C reduction included those where field operations and pesticides only are reduced or eliminated from the management prescription. For example, a negligible reduction occurred in option EF9 (conservation headlands in cereal fields) due to the substitution of pendimethalin + isoproturon with clodinafop-propargyl. There is however the risk of increased herbicide use later in the rotation due to increased weed infestation that may eliminate any CO$_2$ e saving during the cereal crop. A few options increased the net CO$_2$ e emissions and this was generally a small increase below 0.05 t CO$_2$ e ha$^{-1}$ year$^{-1}$. An example is the creation of skylark plots (EF8) where with the exception of no drilling of seed or harvest or post harvest operations there was no requirement to manage the plots differently to the remainder of the field. The application of herbicides resulted in no AGC accumulation through natural regeneration and a loss of AGC equivalent to that contained within the cop during year one.

3.7. On intensive grassland the establishment of input free grass strips (EE4 - EE6) resulted in the greatest reduction in GHG emissions (EDP) relative to the baseline (Figures 3 and 4) with both permanent and non-permanent CO$_2$ e savings (EDP). These options were also indicative of the change to be expected in options such as EE7 (buffering ponds) and EK1 (take field corners out of management). The management of grass strips required few inputs and their non-ploughing and reseeding allowed the establishment of SOC at a greater equilibrium of 440.0 t CO$_2$ e ha$^{-1}$ at an annual accumulation rate of 3.8 t CO$_2$ e ha$^{-1}$ year$^{-1}$ (Figure 4). Where a shift in the management from intensive grassland to semi-improved grassland occurred such as in option EDS a reduction in inputs (mineral N fertiliser in particular) and livestock emissions, mainly from enteric fermentation, resulted but were not entirely eliminated. The non-ploughing and re-seeding of the land allowed a potential increase in the SOC at a rate of 4.61 t CO$_2$ e ha$^{-1}$ year$^{-1}$ to establish a new SOC content of 440.0 t CO$_2$ e ha$^{-1}$ at equilibrium after 32 years. The AGC was predicted to increase by 2.93 t CO$_2$ e ha$^{-1}$ during year one only. Not all options on intensive grassland were calculated to increase or maintain the SOC at the same level and a loss was calculated in options where the tillage frequency was increased for example, the pollen and nectar flower mixtures on grassland (EG3). A loss in SOC from the baseline of 293.3 t CO$_2$ e ha$^{-1}$ to 275.0 t CO$_2$ e ha$^{-1}$ (as modelled for arable land under extensification) was predicted owing to an increase in the tillage frequency. The loss of SOC tends to be exponential and a new equilibrium was reached after an estimated 5 years although the loss was partially offset by an increase in the AGC of 2.93 t CO$_2$ e ha$^{-1}$ year$^{-1}$ during year one only. The permanent reductions in GHG emissions associated with fertiliser manufacture and with emissions from livestock did result in a mean net C reduction of -4.48 t CO$_2$ e ha$^{-1}$ after five years. A similar impact on SOC was calculated for wild birdseed mix (option EG2) although continued application of N fertiliser, albeit at a reduced rate, to maintain seed yield resulted in a smaller reduction in the net GHG emissions (EDP).

3.8. On semi-improved grassland the potential to reduce the GHG emissions (EDP) from inputs compared to intensive grassland was lower due to fewer emissions from the baseline scenario and no potential for a further increase in the SOC at equilibrium. Option EL1 (field corner management (LFA land)) that removed livestock and all inputs (Figures 3 and 4) illustrates the maximum reduction that may be obtained on such land within the ELS. Options EK2 and EL2 (permanent grassland with low inputs) on lowland and upland grassland respectively eliminated only the fuel consumption associated with chain hawring (Figure 4). The management of rush pastures (options EK4 and EL4) required an additional mowing operation on 33% of the area relative to the baseline and produced a slight increase in the emissions. In most cases any increase was relatively minor in comparison to the reductions achieved from other options. The SOC was at an assumed maximum and this maximum was maintained.
3.9. The potential for any reduction on unimproved grassland was smaller still and there was no change in management assumed for option ED4 (scrub on archaeological sites) except an additional mowing operation (Table 4) that was required where scrub encroachment was not contained by grazing. Options EL5 (enclosed rough grazing) and EL6 (moorland and rough grazing) on upland rough grassland were also both largely unchanged relative to the unimproved grassland baseline on undrained peat soil grazed by sheep, though EL6 may have negligible emissions associated with the use of a brushwood cutter to trim gorse. The main difference resulted from supplementary feed applied solely as concentrates with no silage (the management description specified not to supplementary feed using silage or other forage wrapped in plastic) that increased emissions by 0.04 t CO$_2$e ha$^{-1}$.

3.2.2. Higher Level Scheme

3.10. Certain HLS options had identical GHG mitigating properties to the options described previously within the ELS scheme, for example the creation of grass strips. The following section focuses upon those options that have not been described under ELS although they are ranked for comparison in Appendix 3 Table 3.2. The HLS options included the creation of habitat, its restoration or its maintenance. The greatest CO$_2$e savings$_{(EDP)}$ occurred in options that changed the land use from arable land or intensively managed grassland to a semi-natural habitat, namely the habitat creation options. Figure 5 summarises the net change in GHG emissions$_{(EDP)}$ for selected options with arable, intensive, semi-improved or unimproved grassland baseline scenarios. The semi-natural habitat baseline scenarios (options HQ7 to HO3 in Figure 5) (described in Appendix 1.2) were representative of land covered with a proportion of the desired habitat that underwent restoration or maintenance where changes in the GHG emissions$_{(EDP)}$ tended to be smaller. Their current management regime was such that emissions are low and the SOC close to its maximum.

![Figure 5. The GHG emissions (t CO$_2$e ha$^{-1}$year$^{-1}$) from land managed under the original baseline scenario (grouped by winter wheat, intensive grassland grazed by dairy cattle, semi-improved and unimproved grassland and semi-natural habitat), the mean per year after five years for selected HLS options and the resultant change in GHG emissions$_{(EDP)}$.](image)

3.11. There is potential for a significant decrease in soil CO$_2$e emissions in options where the water table is restored on peat soils (Figures 4 and 5). The creation of fen on arable land removed all agrochemical inputs while the growth of trees on 2% of the area allowed a gain in AGC. Most importantly the management change of this option was calculated to prevent further loss...
of CO$_2$ from the oxidation of the peat substrate where a mean net CO$_2$e reduction of -17.46 t CO$_2$e ha$^{-1}$year$^{-1}$ was calculated after five years.

3.12. The greatest reductions in GHG emissions$_{(EDP)}$ on arable land within the ELS have been described in section 3.2.1 included the creation of grass strips and similar reductions were calculated for options such as HE10 (floristically enhanced grass margin). Several options changed the land managed as arable to that of unimproved grassland or similar and the predicted changes in GHG emissions$_{(EDP)}$ for such options are illustrated by option HK13 (creation of wet grassland for breeding waders on arable land). The emissions decreased with the exception of those associated with the addition of cattle, in particular the 0.08 t CO$_2$e ha$^{-1}$year$^{-1}$ for the manufacture of feed and 0.37 t CO$_2$e ha$^{-1}$year$^{-1}$ from enteric fermentation (Figure 5). Other options with similar GHG mitigation$_{(EDP)}$ properties on arable land included the creation of wood pasture (option HC14) (with additional AGC as trees on 10% of the area), the reversion to unfertilised grassland to prevent erosion / run-off (option HJ3), in field grass areas to prevent erosion or run-off (option HJ5) and the creation of lowland heathland on arable land (option HO4).

3.13. The options that maintained the land within cultivation mostly did not increase the SOC with the exception of option HD6 (crop establishment by direct drilling). This option had identical management as the winter wheat baseline scenario except the tillage operations were absent and a direct drill was used. The SOC accumulation has been calculated as 0.7 t CO$_2$e ha$^{-1}$year$^{-1}$ with an equilibrium of 275.0 t CO$_2$e ha$^{-1}$ reached after 26 years. The emissions of N$_2$O were calculated to increase by 0.49 t CO$_2$e ha$^{-1}$year$^{-1}$. Post year 26 there was no further SOC accumulation however the increased emissions of N$_2$O were calculated to continue as was the reduction in GHG emissions$_{(EDP)}$ of 0.15 t CO$_2$e ha$^{-1}$year$^{-1}$ from the elimination of tillage operations. Of the remaining options where land was maintained within cultivation the reductions were permanent through either the total elimination of or a reduction in agro-chemical inputs and the use of machinery to varying degrees. They included option HF13 (fallow plots for ground-nesting birds) where no agro-chemical inputs were applied (Figures 4 and 5) and option HG7 (low input spring cereal to retain or re-create an arable mosaic) that had reduced fertiliser and herbicide use.

3.14. The HLS options on intensive grassland have been described in the ELS with the exception of option HE11 (enhanced buffer strips on intensive grassland). This option was protected from grazing and required re-establishment when the wild flower cover decreased and the management of this scenario removed livestock and their associated emissions, re-established the cover every 8 years (the same period as grass reseeding on the intensive grassland baseline scenario) and did not apply fertilisers. The SOC at equilibrium remained unchanged, a more frequent establishment regime would in all probability result in a reduction of the SOC at equilibrium to 275.0 t CO$_2$e ha$^{-1}$ (agricultural extensification) within five years$^{15,67}$ as calculated for the pollen and birdseed mixtures.

3.15. Most of the HLS options implemented on a semi-improved grassland baseline scenario reduced the GHG emissions$_{(EDP)}$ through a reduction in the stocking rates and fertiliser inputs. Further reductions as a result of increased C storage as SOC were not calculated since the attainable maximum was already assumed. The option for woodland creation (HC10 outside the LFA) offered potential to significantly increase the AGC accumulation (10.27 t CO$_2$e ha$^{-1}$) (Table 5) negligible soil disturbance during the establishment of the woodland did not result in a loss of SOC$^{13}$. The removal of stock allowed permanent CO$_2$e savings$_{(EDP)}$ (Figure 4). The creation of traditional orchards (option HC21) allowed the equivalent of woodland (pre year 50) to be planted on 20% of the area with an associated AGC accumulation of 2.05 t CO$_2$e ha$^{-1}$ up to year 50 while stock were reduced to levels of unimproved grassland. The restoration of moorland (option HL10) on a semi-improved upland grassland (drained peat soil) specified the blocking of grips. An impact of this is the probable restoration of the water table and prevention of further oxidation of peat at 7.3 t CO$_2$e ha$^{-1}$ which has been included in the calculations. The effectiveness of such management and the time elapsed between the reflooding of peat and the arrest of peat oxidation is however currently unknown$^{13}$. The blocking of grips has also been found to reduce the loss of DOC from such habitats$^{76}$. A variety of techniques were described in the management prescription including burning, ploughing, treatment with herbicide and the spreading of heather. Tillage on upland peat was considered unlikely due to the potential to damage soil structure this method therefore was
The establishment of vegetation on previously bare peat is also likely to prevent soil erosion\(^{79,80}\). Calculations have been made for 33% of the area treated with a herbicide to allow regeneration, 33% created from the spreading of heather or heathland seed or cuttings with the equivalent of a fertiliser spreader (125 kg ha\(^{-1}\) spread) and the remainder burnt. The vegetation underwent a 10 year regeneration cycle thus the AGC accumulation continued during this period. The land was assumed grazed by sheep in order to prevent compaction\(^8^1\) at unimproved grassland stocking rates. The prevention of further oxidation of peat was also calculated in option HL11 (creation of upland heathland), HL10 (restoration of moorland) and HL8 (rough grazing for birds). The remaining options implemented on semi-improved grassland baseline scenarios in general reduced the stocking levels and inputs to levels of the unimproved grassland baseline scenario. They included the creation of inter-tidal and saline habitat on grassland (HP4) (except the flooding of land for this option resulted in net CH\(_4\) emissions), HK7 (restoration of species-rich, semi-natural grassland), HK11 (restoration of wet grassland for breeding waders) and HK12 (restoration of wet grassland for wintering waders and wildfowl).

3.16. The majority of options with an unimproved grassland baseline scenario did not reduce emissions significantly but maintained existing C stores as SOC. The exception was option HC9 (Creation of woodland inside the LFA) that as described previously for option HC10 increased the AGC and removed the emissions from livestock albeit of a low stocking rate (Figure 5).

3.17. Most of the restoration options did not have such a large C mitigation\(_{\text{EDP}}\) potential as the habitat creation options since a proportion of the land was already of the desired habitat type and therefore the management not altered. The presence of existing habitat meant the baseline scenarios had to be constructed individually for these options as opposed to using those described previously such as winter wheat or semi-improved grassland. The greatest reduction in GHG emissions\(_{\text{EDP}}\) was calculated for restoration of habitats on drained peat soils such as fen and lowland raised bog (HQ7 and HQ10) where the reflooding of land reversed the emission of CO\(_2\) from oxidising peat. Many restoration options had an initial phase to remove undesirable habitat such as encroaching scrub that resulted in loss of AGC during year one. For example, the restoration of reed bed described in option HQ4 required that the land had an existing good cover of reeds (90% post year 5). Scrub was removed from 10% of the area and during year one there was a loss of AGC associated with this although the 10% of the area was restored to reed cover where an accumulation of AGC occurred for the first five years compensated for the losses from the initial scrub removal. A net increase in emissions (0.11 t CO\(_2\)e ha\(^{-1}\) year\(^{-1}\)) occurred for each year after restoration relative to the scrub baseline scenario on account of the flooding of land that caused net CH\(_4\) emissions from soil of 0.53 t CO\(_2\)e ha\(^{-1}\) year\(^{-1}\). The restoration of orchards (option HC20), traditional water meadow (option HD11) and the restoration of lowland heathland on neglected sites (option HO2) required the removal of scrub during year one and the grazing of the restored previously ungrazed area at stocking rates the same as unimproved grassland. The regeneration of Calluna on heathland accumulated the equivalent of 0.62 t CO\(_2\)e ha\(^{-1}\) year\(^{-1}\) as AGC (10% was burnt each year rotationally) up to year ten. The restoration of sand dunes (option HP2) restored unimproved grassland grazing levels to a previously ungrazed area with no scrub removal. The restoration of forestry areas to lowland heathland (option HO3) resulted in the largest increase in net CO\(_2\)e emissions due to the loss of AGC within the timber that was not replaced through the re-planting of new trees post harvest and substituted by the regeneration of Calluna. There was a decrease in the permanent CO\(_2\)e emissions associated with the loading, harvest and the transportation of timber.

3.2.3. Organic Entry / Higher Level Scheme

3.18. The net GHG emissions from the OELS on organic land are summarised in Figure 6 where a change in management from cultivated land to the maintenance of woodland edges (option OC4) and grass buffer strips (options OE1 – OE3) resulted in the greatest CO\(_2\)e savings\(_{\text{EDP}}\) (Figures 4 and 6). This was also applicable to options with similar management strategies such as OF1 (field corner management) and OF7 (beetle banks). The main reductions in permanent CO\(_2\)e emissions were from crop nutrition (the non-application of lime and no machinery operations associated with the management of a grass / clover ley), the elimination...
of ploughing and other machinery operations such as mechanical weeding (Figure 4). The soil \( \text{N}_2\text{O} \) emissions decreased to levels of unfertilised grassland. The removal of land from tillage allowed the accumulation of SOC to a potential equilibrium of 440.0 t CO\(_2\)e ha\(^{-1}\). Where management shifted from cultivated land to semi-improved grassland such as in option OD2 (take archaeological features out of cultivation) lime was still applied albeit at a lower rate (Figure 4). The rotation within organic cultivated land already included livestock the emissions of which were not included with the winter wheat baseline scenario, only a proportion of the maintenance of the grass / clover ley (Appendix A1.3.1.). The grazing of land previously managed as organic winter wheat if stocked at levels of the organic semi-improved grassland baseline scenario resulted in an increase in the permanent GHG emissions\(^{(EDP)}\) and net CO\(_2\)e emissions overall after the accumulation of SOC stopped post year 55. It must be noted however that this calculation was for just one crop and does not take account of other crops that may have greater GHG emissions during their production.

Figure 6. The GHG emissions (t CO\(_2\)e ha\(^{-1}\)year\(^{-1}\)) from land managed under the original baseline scenario (grouped by winter wheat, intensive grassland grazed by dairy cattle, semi-improved grassland and unimproved grassland), the mean per year after five years for selected OELS options and the resultant change in GHG emissions\(^{(EDP)}\).

3.19. The recent conversion of organic land within the OELS assumed that the SOC had the potential to increase from 256.7 t CO\(_2\)e ha\(^{-1}\) to 275.0 t CO\(_2\)e ha\(^{-1}\) in all options that maintained land within cultivation due to the inclusion of a three year grass / clover ley within the rotation. All options on cultivated organic land therefore were calculated to accumulate SOC at a rate of 2.62 t CO\(_2\)e ha\(^{-1}\)\(\cdot\)year\(^{-1}\) and this dominated the net CO\(_2\)e savings\(^{(EDP)}\) for the first seven years while the reductions post year seven were permanent (Figure 4). No lime was applied to the pollen and nectar flower mixture (option OF4) and the biennial tillage regime resulted in a decrease in GHG emissions\(^{(EDP)}\) from decreased fuel consumption and machinery depreciation. The wild bird seed mixture (option OF2) also underwent tillage biennially but required the same inputs for crop nutrition as the baseline rotation scenario. Smaller reductions were calculated for this option relative to OF4 as a consequence. Natural regeneration and the accumulation of AGC was assumed to occur during year one in non-cropped areas such as skylark plots (option OF8) although the AGC accumulated was lower than that contained within the crop (-0.12 t CO\(_2\)e ha\(^{-1}\)).

3.20. On organic grassland grazed by dairy cows the greatest potential for a reduction in GHG emissions\(^{(EDP)}\) resulted from the creation of grass buffer strips (options OE4-OE6). Under this management regime there was no ploughing or re-seeding and no inputs associated with crop
nutrition, other field operations or from livestock. The SOC had potential to increase from 293.3 to 440.0 t CO\textsubscript{2}e ha\textsuperscript{-1} at equilibrium (Figures 4 and 6). The pollen and nectar mix (option OF2) and wild birdseed mix (option OF4) both had a net reduction in the permanent GHG emissions\textsubscript{EDP} mainly as a result of the removal of livestock. A loss of SOC occurred in both options however due to an increase in the tillage frequency with an equilibrium re-established at 275.0 t CO\textsubscript{2}e ha\textsuperscript{-1}. This loss was less than the permanent CO\textsubscript{2}e savings\textsubscript{EDP} consequently a reduction in GHG emissions\textsubscript{EDP} occurred overall which further increased post year five when the loss of SOC ceased.

3.21. The options implemented on semi-improved and unimproved organic grassland were calculated to reduce emissions through permanent saving\textsubscript{EDP} since the SOC was at a maximum at equilibrium of 440.0 t CO\textsubscript{2}e ha\textsuperscript{-1}. Options with the greatest potential for reduction included OL1 (field corner management (LFA land)) (Figure 6) that reduced the stocking rate and eliminated chain harrowing and lime application. The reductions associated with other options on these two organic baseline scenarios removed either mechanical operations such as chain harrowing (option OL2 manage permanent in-bye grassland with low inputs) or lime (option OL3 manage permanent in-bye pasture with very low inputs). The option OL5 (enclosed rough grazing) did not supplementary feed and option OK4 (management of rush pastures (outside the LFA)) introduced mowing on one third of the area resulting in a small increase in emissions although this was relatively small (Figure 6).

3.2.4. Farm Management Plans

3.23. The highly farm specific nature of farm management plans rendered it difficult to quantify the exact impact on GHG emissions. The plans aim to optimise and thus reduce inputs therefore the impact will be to reduce GHG emissions, the fertiliser management plans that optimise the application of fertiliser N in particular. These management plans have important implications for minimising the GHG emissions per tonne of yield.

3.2.5. Supplementary Options

3.24. The supplementary options are in addition to the main options. Those that may contribute further to the overall GHG balance\textsubscript{EDP} of ES included supplement HL8 (nil fertiliser supplement) for use with option HJ6 (preventing erosion or run-off from intensively managed improved grassland). This would reduce N fertiliser by a further mean 25 kg N ha\textsuperscript{-1} that is applied to the semi-improved grassland management regime that the improved grassland baseline is reverted to under option HJ6. The impact of supplement HL15 (seasonal livestock exclusion) depends upon the location of the stock during the period that they are excluded. The housing of animals indoors impacts upon the location of the stock during the period that they are excluded. The removal of stock from land at risk of flooding when the soil is anaerobic may reduce the N input to the land in deposition and ultimately reduce the N\textsubscript{2}O emissions from denitrification\textsuperscript{82}. The supplements HP10 and HP11 extensive / removal of livestock on saltmarsh further reduced the emissions associated with livestock. With respect to uptake however, only HL15 was applied to a significant area of 6662 ha. The planting of hedgerows or tree whips will allow the accumulation of additional AGC.

3.3. Climate change mitigation\textsubscript{EDP} under current levels of uptake

3.25. The ES options, the ESA and CSS options and their ES equivalent, and the area of land currently managed within each option have been provided by Natural England. Under current levels of uptake ES has resulted in an estimated decrease of between 3,460,000 and 3,779,000 t CO\textsubscript{2}e year\textsuperscript{-1} (the mean of years one and 25 respectively) (Table 6).
Table 6. The total C mitigation potential of ES, CSS and ESA (t CO$_2$e) and estimated percent reduction of UK GHG emissions. The percent change is calculated for the mean C reduction per year for years 5, 25, 50 and 100.

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<td>-3449400</td>
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<td>UK 2005 Total</td>
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<td>Percentage 2005 emissions</td>
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<td>-0.58</td>
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<td>-0.53</td>
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<tr>
<td>Percentage change from base year</td>
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<td>-0.49</td>
<td>-0.49</td>
<td>-0.48</td>
<td>-0.45</td>
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</table>

1 Including net CO$_2$ from Land Use Change Factor.
2 The entire time series is revised each year to take account of methodological improvements in the UK emissions inventory. The baseline and target figures will therefore also change each year, although the percentage reductions required to meet the targets are fixed. This figure is quoted from the 2005 inventory.

The Kyoto Protocol recognises land use, land use change and forestry (LULUCF) activities as a method to increase the C stored within land and ultimately reduce atmospheric CO$_2$ emissions, although its main objective is to reduce GHG emissions at source. Under Article 3.3 of the Kyoto Protocol, the C sequestered in new forests planted since 1990 is included within the reduction targets of developed countries. Under Article 3.4 of the Kyoto Protocol, Parties can elect additional human-induced activities related to LULUCF, specifically either forest management, cropland management, grazing land management and re-vegetation, to be included in its accounting for the first commitment period. Parties may choose to include any of these activities to help meet their emission targets, and the choice is then fixed for the first commitment period. Net removals of greenhouse gases from eligible LULUCF activities generate removal units (RMUs) that may be used to meet emission targets. The UK has elected forest management. Much of the C sequestered within ES schemes is applicable to grassland and cropland management which the UK has not elected. An estimate of the potential contribution of ES (emissions and C sequestered inclusive) to the Kyoto target has been included in Table 6 for illustrative purposes only. This is between 0.44 and 0.49% of the 1990 Kyoto baseline or between 0.53 and 0.58% of the 2005 UK GHG emissions (excluding any contributions to climate change from displaced production).

The change has resulted mainly from the creation of new habitats and a reduction in inputs on arable or improved grassland systems. The reductions are however calculated for the continued management under each option. The reversion to the original baseline will inevitably result in the loss of the SOC and AGC gained over the duration of the option. The C stored within habitats that have undergone restoration or are managed under maintenance options have not been included since it was assumed the C was already within storage from the beginning of the implementation of ES and therefore not contributing to a further reduction in GHG emissions. The preservation of such C stores is important since alteration to a management regime where an equilibrium with a lower SOC content is established will result in C loss as CO$_2$ emissions.

3.4. CO$_2$e savings relative to points per ELS and OELS option

3.26. The points are allocated to options based upon the calculated income foregone up to a maximum of 100%. In general the options with the greatest CO$_2$e savings also had the largest points allocation.
4.0. DISCUSSION

4.1. The method used serves as a guide to the potential impact that ES may have on GHG emissions, both positive and negative, within the UK relative to previous methods of land management. A baseline set of management conditions has been defined in order to provide a reference point against which any changes in land management under ES may be compared. The following require consideration:

1. It is acknowledged that the results would benefit from an uncertainty analysis to account for spatial variability and the impact different soil types, increased or decreased rainfall and variation in the farming practices defined within the baseline conditions may have on the calculated change in emissions for each option. Such variations would further add to the accuracy of the results that have been aggregated to the national scale based upon the uptake of each option. An uncertainty analysis was not possible within the project time-scale and typical scenarios have been constructed as far as possible.

2. The results do not account for a displacement in production within the calculated GHG balance. This may be firstly, the impact of producing and importing the same agricultural commodity from another country to replace any commodity where production has been reduced as a consequence of converting the land into an ES agreement. It is estimated that the UK is currently 72% self-sufficient for the agricultural commodities it is capable of producing itself. The removal of a proportion of productive agricultural land within England as a consequence of the undertaking of ES agreements may displace that production outside of the UK. At the time of writing the impact of imported agricultural goods on GHG emissions reported by previous analyses had been concluded to be insufficiently robust to allow a direct like for like comparison. In response an analysis of the impact of UK versus overseas supply chains is currently the subject of Defra Project FO0103, the results of which are not available at the time of writing. Not all ES options necessitate that a reduction in production occurs but it is recommended that it be taken into account where applicable and when suitable data becomes available. Secondly, displacement may occur on the same farm whereby output is increased within other areas of the same farm that in turn neutralises or reduces any potential reduction in GHG emissions from the specified change of land management. Displacement of production onto other farms within the U.K. would have a similar effect. Displacement of production overseas may reduce the U.K. GHG inventory without necessarily reducing the overall global GHG emissions. Inventorisation of altered emissions, i.e. whether amended emissions would be captured by current inventory methodology, is not covered in this report.

4.2. For most of the options within ES a reduction in the GHG emissions relative to the baseline management scenario has been calculated. This decrease arose from two mechanisms, the first of which was a reduction in the source of emissions (permanent CO$_2$e savings). The main source of these emissions in the baseline scenarios considered were the use of inorganic N fertiliser, N$_2$O emissions from soil, fossil fuel consumption from the use machinery (in particular deeper tillage operations and the transportation of bulky materials), CH$_4$ from the enteric fermentation of livestock and CH$_4$ and N$_2$O emissions from livestock manures. The second mechanism by which CO$_2$e savings were made through ES were non-permanent and resulted from an increase in the C stored within the land when at equilibrium either as SOC or AGC relative to the baseline scenario. The accumulation of C does not occur over an indefinite period and stops upon reaching the equilibrium, which is determined by the method of land management. Any C gained may potentially be lost to the atmosphere if the original management regime is re-instated.

4.3. The current GHG balance of each option relative to the baseline, accounting for the factors described in Section 2 and their relevance to the option management description has been estimated. The options have been grouped by their similarity in the estimated GHG balance in Section 3 where they are sub-divided into four categories. The key specified management requirements that have impacted on the calculated GHG balance for each option are stated in Appendix 2 and this section examines them in greater detail. Some ES options per unit may have a lower net GHG balance solely because of their small size (for example the hedgerow management options per 100m length). The ES options have been grouped by their calculated GHG balance per ha of option for the purpose of the discussion.

4.4. The first category of options and those with the greatest reduction in the GHG balance based upon the 5 year average (which is compatible with the Kyoto accounting period and the
current length of management agreements for ELS) is a permanent change in land use from an arable or improved grassland baseline to a management scenario with virtually zero inputs (land completely removed from production). The 5 year mean difference in carbon flux$_{(EDP)}$ for the ELS, HLS and OELS ranged from -17.5 to -5.4 t CO$_2$e ha$^{-1}$ year$^{-1}$. The contribution of accumulated SOC to this change was typically between 3.3 and 4.0 t CO$_2$e ha$^{-1}$year$^{-1}$ on cultivated land and improved grassland respectively. The increase in AGC was smaller, 0.7 – 2.9 t CO$_2$e ha$^{-1}$year$^{-1}$ respectively during the first year after the change in management only. The remainder of the reduction in the GHG balance$_{(EDP)}$ arose from a reduction of emissions associated with the manufacture of agro-chemicals, fuel to conduct field operations and emissions of N$_2$O from soil. The removal of livestock or a reduction in stocking rates reduced the emissions of CH$_4$ from enteric fermentation and manures. Of the options currently available within ES the management specifications within the agreement conducive with this change is illustrated by:

a) Options EE4 / EE5 / EE6 (grass buffer strips on grassland) that specify: ‘Strips must not receive any fertilisers or manure. Apply herbicides only to spot treat or weed wipe. After the first 12 months of your agreement, cut buffer strips only to control woody growth, and no more than one year in five (where next to woodland, one year in ten). Do not poach or overgraze the buffer strip’ (it was assumed that given the strips were permanent and no fertilisers permitted a proportional reduction in stocking rate thus emissions from livestock were eliminated). Buffer strips on cultivated land are managed identically with the exception of Option EE3 that stipulates ‘after the first 12 months of your agreement, cut the 3 m next to the crop edge annually after mid July. Only cut the other 3 m to control woody growth, and no more than one year in five (where next to woodland, one year in ten)’. For these options there are no fertilisers, cultivation or disturbance of the soil and a restricted use of pesticides (targeted application of herbicides only) and infrequent mowing. There is little potential to reduce the GHG balance$_{(EDP)}$ of such options further unless the 3 m of option EE3 adjacent to the crop is no longer mown annually or there is no specification to control woody growth post year one. For example, options EC4/HC4/OC4 (Maintenance of woodland edges) specify ‘to trim no more than one third of the shrubby growth in any one calendar year’. In contrast option EF7 (Beetle banks) specifies ‘only cut as necessary to prevent the encroachment of woody and suckering species’. Options EE7/EE8 (Buffering in-field ponds in improved permanent grassland and arable land): ‘may allow some scrub to develop, but this must be around less than half of the pond margin’. There is potential for scrub to be allowed to develop around a greater proportion of the margin. The planting of trees is another alternative however this would be administered mainly via Forestry Commission Schemes rather than ES. Of the grass buffer strips those 6 m in width (options EE3/HE3/OE3 and EE6/HE6/OE6) are preferred due to the smaller boundary length that is required to maximise the area implemented. In order for this option to maximise the reduction in the GHG balance$_{(EDP)}$ it must remain as a permanent grass strip. Reversion to the original land use is likely to result in the loss of any C accumulated within the soil to the atmosphere. Should reversion occur the permanent CO$_2$e savings$_{(EDP)}$ from a reduction in the inputs of agro-chemicals during the period of the agreement are also close to the potential maximum possible. The length of an agreement is currently five years. Should the strips (or similar) on cultivated land be returned to production after this period any contribution to the soil nitrogen supply as a result of ploughing in the grass should be accounted for in the fertiliser recommendations to the following crop. There are additional benefits such as the prevention of soil erosion$^{75,76}$ and acting as a reservoir for beneficial insects$^{88}$ that may promote a reduction in the number of insecticide applications. A reference is made in these options and many others not to allow the ground to become poached, for example, ‘Graze carefully to minimise poaching and soil erosion’. The poaching of ground by livestock creates anaerobic conditions within the soil, and wet soils are more vulnerable$^{82}$. The risk is further increased by greater stock densities whereby greater quantities of N are deposited with potential to increase the emissions of N$_2$O as a result of denitrification within the anaerobic soil conditions$^{10,82}$. The emissions of N$_2$O that result from poached soils have yet to be fully quantified$^{82}$ and as a consequence they have not been included in the calculations. The inclusion of a requirement to avoid poaching within the management specifications is however conducive with minimising agricultural GHG emissions. Certain options, for example the creation of grasslands for wading birds (options HK 13 and 14) had a slightly smaller reduction in GHG emissions$_{(EDP)}$ (-6 t CO$_2$e ha$^{-1}$ year$^{-1}$) compared to the buffer strips on arable land due to additional emissions associated with the grazing of low numbers of stock. The adoption of such options, unlike grass buffer strips, is limited to certain parts of the country.
b) The options to maintain hedgerows require a buffer zone between the hedge and the crop and the management of this buffer zone is identical to the grass strips discussed previously. The management of the hedgerow itself may differ depending upon the choice of option. Option EB3/OB3 (Enhanced hedgerow management) states: ‘Maintain hedges to a height which is customary to the local landscape, but no less than 2 m. A mixture of heights and widths will provide the best range of habitat. You may use this option to manage hedges that are less than 2 m high at the start of the agreement, but in this case the hedge must be allowed to grow up to the required height’. Option EB2/OB2 (hedgerow management) states: ‘Hedges should be maintained to a height which is customary to the local landscape, but no less than 1.5 m. A mixture of heights and widths will provide the best range of habitat. You may use this option to manage hedges that are less than 2 m high at the start of the agreement, but in this case the hedge must be allowed to grow up to the required height’. A higher specified minimum height as given for option EB3/OB3 allows a greater quantity of AGC at equilibrium to be established. Constraints exist for this option however with respect to the need for ownership of both sides of the hedgerow. Option HB12 (maintenance of hedgerows of very high environmental value) states: ‘Promote the development of a balanced tree population, where this is appropriate to the local landscape’ and additional AGC is potentially provided by the presence of trees in the boundary. Any potential gain in AGC is subject to the hedge being lower than the required minimum height when entered into the agreement, and not being reduced in height. The calculations have assumed no change in the AGC of the hedgerow itself (they are maintained at their current height) since some are likely to gain and some be reduced in their mean height. The greatest potential to gain additional C stored within plant biomass in the hedgerow options is provided by a combination of HB12 and EB3/OB3 that include ‘gapping up’ and ‘the planting of new / restoration of hedgerows’ and the supplementary options HR (Hedgerow restoration) and STT (Planting standard parkland / hedgerow tree).

c) Although mainly administered via the Forestry Commission the planting of trees on small areas (a maximum of 1 ha (3 ha any holding)) is possible within ES in options HC09 (Creation of woodland in the LFA) and HC10 (Creation of woodland outside of the LFA). These options are restricted to specific locations within England but have significant potential to increase the AGC component of the land. The calculated GHG balance of these options assumed that the baseline grassland scenario was not ploughed and re-seeded and that the SOC was already at equilibrium (no further gain was likely). The management of this land under ES therefore also needs to be sympathetic to its maintenance through minimal soil disturbance. Management conducive to this is specified such ‘there must be no ploughing or other cultivation such as reseeding, rolling or chain harrowing [unless these are required to establish trees and shrubs and agreed with your Defra adviser / specifically stated in the prescriptions or in the management plan / capital works programme]’. There is therefore little scope to reduce the GHG balance of these options further. Maximising the AGC within the five year time-scale (compatible with the Kyoto accounting period) is assisted by the protection of young trees as specified in option HC14 (Creation of wood pasture), that allows the development of additional AGC on a proportion of the land. It states ‘Prevent damage to trees from livestock [wild mammals / deer / grey squirrels / rabbits / other]. This includes damage caused by browsing, bark stripping, rubbing against trees or guards and soil compaction below canopies. Check, maintain and remove guards and protection as appropriate to prevent tree damage’. The reduction in the GHG balance that create woodland becomes smaller after year 50 when it was assumed that the accumulation of AGC ceases although it is acknowledged that different species mixtures will accumulate C at different rates and potentially store different quantities at equilibrium. The rate of C accumulation within trees is assumed to be constant based upon the mean of the maximum at equilibrium and the time taken to reach this maximum. The accuracy of the calculated GHG balance would be improved by calculating the AGC of individual tree species then taking account of the target species mixtures and percent cover stipulated in the detailed HLS management prescription and associated indicators of success. An option to plant trees that is more generally available to farmers is the supplementary option TSP (Planting tree shrub / whips and transplants) which offers similar potential to accumulate AGC albeit on a small scale.

4.5. The primary objective of the habitat creation / restoration / maintenance options (administered via the HLS) is conservation and biodiversity. Peat soils contain greater quantities of SOC at equilibrium than other soil types however this C may be lost to the atmosphere as CO₂ by oxidation within aerobic conditions created by land drainage. Those
options that preserve or restore the water table and prevent the release of CO\textsubscript{2} from peat soils by re-wetting\textsuperscript{53,82} and maintain the C store have significant potential to reduce GHG emissions. They are however restricted by soil type and location and thus cannot be implemented widely across the countryside. There is also an element of uncertainty as to the effectiveness and the time-scale\textsuperscript{53,82}. The re-wetting of soils creates an anaerobic environment that may prevent further oxidation of C however, as discussed previously, anaerobic conditions also risk increased denitrification and emissions of N\textsubscript{2}O from the soil. During denitrification most of the N emissions may be as dinitrogen (N\textsubscript{2}) gas but a fraction is also released as N\textsubscript{2}O \textsuperscript{35,41}. The fraction of which is estimated to range between 0.01 – 0.06 on sand, clay and loam soils\textsuperscript{41} with a mean value of 0.035 \textsuperscript{17}. On peat soils this fraction is estimated to range between 0.02 – 0.12 with a mean value of 0.07 \textsuperscript{41}. The risk of emissions of N\textsubscript{2}O from denitrification may be greater on peat soils thus where land is re-wetted it is important that the levels of NO\textsubscript{3} within the soil are kept at a minimum. All current options on peat soils specify restrictions of fertilisers: ‘do not apply fertilisers, organic manures or waste materials (including sewage sludge) [unless specifically agreed in writing with a Defra adviser and/or stated in a management plan/capital works programme’. Restrictions are also placed upon cultivations ‘Do not plough, level, roll, re-seed or chain harrow’. Not ploughing such soils prevents further loss of SOC\textsuperscript{12,13,14}. Options on peat soils and their stated management conducive to minimising GHG emissions\textsubscript{SEDPM} include:

a) The restoration of lowland raised bog (HL10): ‘Maintain the water table and water in the existing ditch system with rainfall only. Do not allow tap water onto the bog. Do not dig or turn over peat, without prior written consent from your Defra adviser’. There is an energy requirement and thus GHG emissions associated with the treatment of mains tap water.

b) The creation/restore of fen (options HQ8 and HQ7) states: ‘Do not use poor quality water with high nutrient concentrations to top up water levels. Do not allow any high nutrient load agricultural drains that intercept surface flow or groundwater seepage, to empty into fens’. These two requirements prevent further addition of N to the soil and therefore are a key means to reduce the risk of denitrification. Although the promotion of an increase in AGC through greater tree cover may help maximise the C storage potential of land in other options (for example options HC09 (Creation of woodland in the LFA)), the presence of trees on bogs or fens are likely to inhibit the re-wetting of the peat soil. This will be detrimental to maintaining the levels of SOC and preventing further release of CO\textsubscript{2} to the atmosphere. The current management prescription to ‘Maintain fen in an open condition, with scattered trees and scrub covering no more than [20\%] of the fen area’ therefore is more effective at maximising the C storage potential of such areas than allowing trees or scrub to develop any further cover. Allowing additional AGC on the periphery of the site ‘Manage existing patches of scrub to maximise the length and shelter provided by the scrub margin, and to maintain a diversity of scrub type and shrub age classes’ allows increased AGC where it is not detrimental to the re-wetting objective. Option HQ08 currently states: ‘cut scrub should be stacked or burned’ and this should be preferably stacked.

The supplement HL13 (Moorland re-wetting) is available only on options HL7 - 11: on ‘peat exposures and other sensitive soils, where damage is a potential problem’. In addition to no fertilisers or cultivations the re-wetting of such sites is accompanied by the following key management requirements:

a) The creation/restore of moorland (HL9 and HL10): ‘There must be no signs of burning into the moss, liverwort and lichen layer, or exposure or breaking of the peat surface due to burning’. The burning must be maintained at a superficial level only with no impact upon the soil. The restoration of moorland (option HL10) on a semi-improved upland grassland (drained peat soil) currently specifies a variety of techniques in the management prescription including burning, ploughing, treatment with herbicide and the spreading of heather. Increased tillage, as outlined in section 2 risks an increase in the loss of SOC and this is likely to be exasperated on high C containing soils such as peat. Tillage on upland peat was considered unlikely due to the potential to damage soil structure and this method was not included in the analysis. It is recommended however that reference to it be removed from the management prescription of option HL10 completely. The management also currently states that ‘restoration may also include grip blocking’ but also states ‘there must be no new drainage or modification/improvement to existing drainage systems. Existing drains can be maintained’. Although there is no permitted increase in drainage it would be preferable to block grips (Moorland re-wetting, Supplement HL13) and allow the re-wetting of the previously drained soil in an attempt to prevent further oxidation of the SOC.
b) The restoration of rough grazing for birds (HL8) restricts livestock access during periods when flooding may arise: ‘In order to avoid damage to soil structure, field operations and stocking should not be carried out when the land is waterlogged’.

Where grazing is necessary on peat soils stocking rates should be minimised. The seasonal removal of stock from wet land is cited as offering potential to mitigate GHG emissions through a reduction in the risk of poaching and deposition of N onto soils with predominantly anaerobic conditions\(^2\). The emissions of N\(_2\)O may be increased under such conditions although the quantity needs to be determined\(^2\). It is likely that the current management stipulation of seasonal removal of stock from the land is conducive with reducing the GHG balance\(^{(EDP)}\) of this option. The Creation of upland heathland (HL11) also restricts the time of year grazing may be allowed: ‘Exclude all livestock between 16 August and 14 May’.

c) Options maintenance, restoration and creation of fens and maintenance and restoration of lowland raised bog options HQ6 - HQ10 allow supplement HQ12 (Wetland grazing): ‘Graze [fen / bog] extensively’, ‘[No grazing is allowed outside this period without prior written consent from your Defra adviser]. Supplementary feeding is confined to the feeding of hay / straw / forage roots / concentrates / mineral blocks in fields. Feeders and troughs should not be used; feeding sites should be moved regularly’. The restrictions on stocking rate and the time of year that grazing is allowed will reduce the risk of N\(_2\)O from deposition of N onto soils with anaerobic conditions as described in (b) above\(^2\). The frequent movement of feeding sites will prevent the risk of poaching.

The re-wetting of high C containing soils such as peat offers potential to reduce emissions of CO\(_2\) however this may not always be a practical solution. For example, the management description of option HQ10 (Restoration of lowland raised bog) states: ‘Inadequate rainfall or its retention can make a site less suitable. This is important where the perimeter drainage and water abstraction from underlying aquifers may limit the re-wetting potential of certain sites, in particular where the site is isolated within arable land’. Peat soils may be more vulnerable to losses of N\(_2\)O from denitrification\(^1\) and therefore applications of N to such soils should be avoided. The MAFF (2000)\(^3^9\) fertiliser recommendations currently stipulate lower / zero applications of N to crops on peat soils. Further restrictions on the application of N (through for example supplement HL8 (nil fertiliser supplement)) to peat soils that are not entered into a habitat creation option within the HLS would be preferable.

4.6. The second category of options is cultivated land that remained cultivated but was managed such that C accumulation occurred within the soil and the SOC at equilibrium was increased, namely by a reduction in the frequency of tillage through, for example, the inclusion of a grass / clover ley within the rotation. The GHG balance\(^{(EDP)}\) of this group of options relative to the baseline was reduced by between \(-3.3\) and \(-1.8\) t CO\(_2\)e ha\(^{-1}\) year\(^{-1}\). The contribution of accumulated SOC to this change ranged from 0.2 to 2.6 t CO\(_2\)e ha\(^{-1}\)year\(^{-1}\). The exact magnitude of this potential increase in SOC at equilibrium is currently uncertain however the rate of C accumulation and the SOC at equilibrium is lower than the first category. In addition to the potential increase in the SOC, the reduction in the frequency of tillage operations and the quantity of agro-chemicals applied had associated permanent CO\(_2\)e savings\(^{(EDP)}\) from a reduction in fuel consumption and emissions of N\(_2\)O from soil. Again this was not of the same magnitude as found in category 1. A total loss or partial reduction in yield usually resulted. Selected options that illustrate this category and their management specifications relevant to a reduction in the GHG balance\(^{(EDP)}\) (described for all options in Appendix 2) include:

a) Options EG1/HG1/OG1 (undersown spring cereals) states: ‘The addition of a grass/legume mix as an under storey to the cereal crop will reduce the need for agrochemical inputs. Undersow a spring cereal crop (but not maize) with a grass ley, including at least 10% legume by weight. Keep the under sown plant growth until the cereal crop is harvested. Do not destroy the grass ley before 15 July the following year’. The presence of legumes offers potential to act as a source of N to the following crop which in a conventional arable rotation (EG1/HG1) may allow partial substitution of inorganic N. The quantity of inorganic N and thus any reduction in emissions associated with its manufacture is dictated by the mixture composition\(^3^9\). Grass / legume mixtures that maximise the potential N that may be substituted within a short time period will be of greatest benefit to reducing the GHG balance\(^{(EDP)}\) as a part of this option. Keeping the ley in place until the following year also reduces the frequency of tillage that allows the accumulation of SOC\(^12,13,14\) but at a cost of one years cropping.

b) Options ED3/HD3/OD3 (reduce depth on archaeological features): ‘Avoid deep soil disturbance by using shallow cultivations (i.e. a maximum depth of 10 cm (4 inches)) or no-
till practices' has potential CO$_2$e savings$_{(EDP)}$ due to a reduction in fuel use and an increase in the SOC at equilibrium$^{12,13,14}$. The impact of minimum tillage upon other GHG emissions (increased emissions of N$_2$O from soil due to denitrification) and its potential for 'pollution swapping' has been deemed to be both negligible$^{90}$ or in need of further research$^{92}$. No-till or zero-tillage also offers potential to accumulate SOC and at a faster rate compared to minimum tillage however there is also an increased risk of soil N$_2$O emissions and emissions of a greater magnitude$^{15}$. As a consequence, there may be a net increase in emissions once the accumulation of SOC ceases despite the CO$_2$e savings$_{(EDP)}$ that are derived from decreased fuel consumption$^{15}$. The value of zero-tillage (also specified in option HD6 (crop establishment by direct drilling)) and its adoption globally has been endorsed$^{17}$ despite the uncertainty that surrounds the impact on the emissions of N$_2$O from soil. Due to this uncertainty neither zero or minimum tillage are currently recommended as a means to mitigate agricultural GHG emissions within England. Given that options ED3/HD3 stipulate the use of one of these methods current understanding suggests that it is preferable to use minimum tillage since the potential risk of increased soil N$_2$O emissions and an overall positive GHG balance is less than the use of zero tillage$^{15}$. The risk of emissions of N$_2$O from anaerobic soils via denitrification is reduced in response to a decrease in the application of fertiliser N$^{5,34}$. Where reduced or zero tillage is necessary to achieve option objectives, specifying a restriction of the application of N may be necessary although this will carry a further yield penalty and require a greater payment for income foregone. An alternative would be to combine it with existing lower N input options on cultivated land such as EF2/HF2 (wild bird-seed mixture).

c) EF4/HF4/OF4 (Pollen and nectar flower mixture): 'Sow a mixture of at least three pollen and nectar rich plants (e.g. red clover, alsike clover, bird's-foot-trefoil), with no single species making up more than 70% of the mix. Re-establish the mix as necessary to maintain a sustained pollen and nectar supply. Apply herbicides only to spot treat or weed wipe. Do not apply any other pesticides, fertiliser, manure or lime. To stimulate late flowering, cut half the area to 20 cm in June and the whole area to 10 cm between 15 September and 31 October'. The requirement to re-establish the mixture as necessary decreases the frequency of tillage with potential to accumulate SOC and no inorganic N is necessary due to the presence of clover in the mixture. In order to achieve management objectives frequent cutting is necessary and little more can be done to reduce the GHG balance$_{(EDP)}$ of this option further. Any mixture that permits a greater period between re-establishment is preferable since it may enhance the accumulation of SOC. The return of the crop residues to the soil is also recognised as a means to enhance levels of SOC within cultivated land$^{12,13,14}$ and although this is likely to occur when the mixture is re-established it is not currently stated as a requirement in the management prescription.

d) Option EF6/HF6/OF6 (Over-wintered stubbles) states: 'Bale or chop and spread straw after harvest'. Do not apply pre-harvest desiccants or post-harvest herbicides. Do not apply any pesticides, fertilisers, manure or lime to the stubble'. There are no inputs allowed to the stubble therefore a further reduction is not possible however the incorporation of straw has potential to increase the SOC content of cultivated land$^{12,13,14,15}$. It would be preferable in this option to chop and spread the straw so it can be incorporated into the soil upon establishment of the crop following the stubbles (return C to soil)$^{15}$ rather than be baled and removed.

e) Option EF2/HF2/OF2 (Wild bird seed mixture) stipulates: 'Sow a combination (either as a mixture or in alternate rows) of at least three small-seed bearing crops (e.g. cereal, kale, quinoa, linseed, millet, mustard, fodder radish, borage). Re-establish as necessary to maintain seed production, and re-sow at least every other year. Apply herbicides only to spot treat or weed wipe. Seed treatment to control seedling pests and diseases is permitted where essential for successful establishment. Do not apply any other pesticides. Only apply fertiliser or manure if necessary for establishment'. Restrictions are already placed upon the application of fertilisers and pesticides and these are difficult to decrease further without compromising the main objective to provide seed as feed for birds. This option specifies re-establishment of the crop every other year but any mixture that has potential to increase this period would be preferable (reduced frequency of tillage and increase in SOC). The return of crop residues to the soil upon re-establishment is also preferable$^{12,13,14}$. The seed mix must be comprised of at least three different crop types two of which may potentially be brassica crops (kale and mustard). Brassicas tend to have a different N requirement compared to, for example, a cereal$^{39}$. Although the application of N is specified only if necessary for establishment a requirement to account for different crop
nutrient requirements within the mixture may allow a more targeted application of fertilisers.

f) Option HF12 (Enhanced wild bird seed mix plots (rotational or non-rotational)): ‘Pesticides and fertilisers should only be applied in accordance with guidance from your Defra adviser’. ‘When the mixture is being re-established, removal of the plant cover and cultivation must not take place before [15 March]’. There is a restriction on inputs although their use is not prevented altogether. Maintaining a crop cover during the winter may reduce nitrate leaching\(^9\) and indirect emissions of \(\text{N}_2\text{O}\)\(^5\).

g) Option OU1 (organic management). The OELS options on cultivated land will include a grass / clover ley that is conducive with the accumulation of additional SOC.

4.7. The third category of options included land that remained within its original use with no alteration to the SOC or AGC content (cultivated land remained cultivated without practices listed in category 2, improved grassland remained ploughed and re-seeded, semi-natural / unimproved land was not ploughed). A reduction in the GHG balance\(_{\text{EDP}}\) (-0.8 to 0) arose solely from decreased gaseous emissions since there was no alteration to the SOC or AGC equilibrium. There was a restriction on the quantity and / or timing of the application of inputs of fertilisers or pesticides, or a reduction in stocking rates and permanent \(\text{CO}_2\)e savings\(_{\text{EDP}}\) from a reduction in fuel consumption, emissions of \(\text{N}_2\text{O}\) from soil and \(\text{CH}_4\) from livestock enteric fermentation and manures.

Examples on cultivated land include:

a) EF10 (Conservation headlands in cereal fields with no fertilisers or manure): ‘do not apply fertiliser or manure to the headland between harvest of the previous crop and harvest of the headland’. All other management with a potential to impact the GHG balance\(_{\text{EDP}}\) (such as the tillage regime) remains unchanged.

b) EF9 (Conservation headlands in cereal fields) / EG4 (Cereals for whole crop silage followed by over-wintered stubbles): there is no change relative to the baseline scenario except for restrictions on pesticides. ‘Do not apply insecticides between 15 March and the following harvest. For broad-leaved weeds use only amidosulfuron and only between 1 February and 31 March. For grass weeds use only the following active ingredients: tri-allate, fenoxaprop-\(P\)-ethyl, dicloflop-methyl + fenoxaprop-\(P\)-ethyl, tralkoxydim or clodinafop-propargyl’.

c) EG5 (Brassica fodder crops followed by over-wintered stubbles): a smaller quantity of fertiliser is applied relative to the baseline and there is a requirement to ‘graze carefully to minimise poaching and soil erosion’. It would be beneficial to highlight that \(N\), \(P\) and \(K\) from deposition of grazing livestock will be available to the following spring cereal crop and needs to be accounted for in the fertiliser recommendations.

Previously Category 1 included the creation or restoration of habitats on peat soils that re-wet the soil and potentially prevent further loss of SOC. The maintenance options on peat soils do not alter the SOC but prevent potential loss as \(\text{CO}_2\) due to oxidation through maintenance of the water table\(^53,82\). No ploughing or re-seeding is permitted and most do not allow the addition of further \(N\). These options and the stipulated management conducive to minimising their GHG balance\(_{\text{EDP}}\) include:

a) EL5 (Enclosed rough grazing): ‘areas of enclosed land of less than 15 ha used exclusively for grazing, of which the majority has not been drained, re-seeded or regularly cultivated. Do not apply fertiliser, manure, lime or slag’.

b) EL6 (Moorland and rough grazing): ‘Protect permanently waterlogged wetlands, including peat bogs and other mires, and hillside flushes. Do not install any new land drainage or modify any existing drainage that would increase run-off. Do not remove any peat or sediment from drainage channels. Do not apply fertiliser, manure, lime or slag’.

c) HL7 (Maintenance of rough grazing for birds): ‘potentially support populations of upland birds (normally waders) and have the potential to develop the appropriate conditions e.g. wet field conditions in March/April. Where agreed in writing with your Defra adviser, block existing surface drains, ditches and grips to create or extend areas of flush or wet, marshy grassland vegetation’. The application of limited quantities of \(N\) is permitted: ‘Well-rotted farmyard manure may be applied at a maximum rate of [12.5] tonnes/ha/yr. In addition/alternatively, inorganic nitrogen fertiliser may be applied at max rate of 50 kg/ha \(N\), unless this would be higher than your existing application rate’. On peat soils it is preferable not to apply inorganic \(N\) or manures.

d) HQ6 (Maintenance of fen): ‘Do not allow any high nutrient load agricultural drains that intercept surface flow or groundwater seepage, to empty into fens. Do not use poor quality water with high nutrient concentrations to top up water levels. There must be no application
of nutrients such as fertilisers, organic manures or waste materials (including sewage sludge).

e) HQ9 (Maintenance of lowland raised bog): ‘Maintain the water table and water in the existing ditch system with rainfall only. Do not allow tap water onto the bog. Do not dig or turn over peat, without prior written consent from your Defra adviser. There must be no application of nutrients such as fertilisers, organic manures or waste materials (including sewage sludge).’

The examples on permanent grassland stipulate that fertiliser and pesticide inputs be restricted (may be subject to approval from a Defra advisor), applications of herbicides must be targeted, no cultivations and there is reference to avoiding poaching and damage to soil structure. On grassland that may be flooded at certain times of the year there are restrictions on the grazing of livestock at certain times of the year. A number of low input grassland options permit the application of FYM, either as an alternative to inorganic N, in conjunction with the application of inorganic N or as the sole source of N. Such options also include the maintenance of existing SOC and AGC on, for example, semi-improved or unimproved grassland and where any loss of C to levels at equilibrium that may be expected on cultivated land or improved grassland is prevented. The restoration and maintenance options on grassland within the HLS have proven reasonably popular among farmers since they are relatively easy to adopt and so moderate amounts of land have been entered into agreements. For example options HK 6, 7, 9 – 12, 15 and 16 – 17 have a combined total of 13,823 ha within agreements. Such options may however risk the displacement of stock onto other areas of the farm with no overall reduction in livestock emissions.

a) EK3/HK3/OK3 Permanent grassland with very low inputs / EL3/HL3/OL3 Manage in-bye pasture and meadows with very low inputs: ‘may apply up to 12.5 tonnes/ha (5 t/acre) of FYM a year in a single application, but only where the grassland is regularly cut. FYM must not be applied between 1 April and 30 June to avoid damage to ground nesting bird sites. No other type of fertiliser or manure may be applied’.

b) EK2/HK2 Permanent grassland with low inputs / EK4/HK4 Management of rush pastures (outside the LFA) / EL2 Manage permanent in-bye grassland with low inputs / EL4 Management of rush pastures (LFA land): ‘Do not apply more than 50 kg/ha nitrogen per year as inorganic fertiliser. Where animal manures are applied, either alone or in addition to inorganic fertiliser, the total rate of nitrogen must not exceed 100 kg/ha N per year. Do not apply between 1 April and 31 May’. Do not cultivate. Supplementary feeding is allowed, but move feeders as often as required to avoid excessive poaching and do not feed on or next to steep slopes or watercourses. Manage by light grazing and/or cutting. Apply herbicides only to spot treat or weed wipe’.

c) HK11 (Restoration of wet grassland for breeding waders): ‘Lime may be applied subject to a soil test showing the need [and agreed with your Defra adviser]. Field operations and stocking must not damage the soil structure or cause heavy poaching. Small areas of bare ground on up to [5%] of the field are acceptable. Take particular care when the land is waterlogged. Do not graze between [30 November and 28 February unless you have agreed a stocking and supplementary feeding strategy with your Defra adviser]. Do not apply fertilisers, organic manures or waste materials (including sewage sludge) [unless specifically agreed in writing with your Defra adviser and / or stated in a management plan / capital works programme]. Well-rotted farmyard manure may be applied at a maximum rate of [12.5] tonnes/ha/yr, but not between 1 Apr and 30 June or within 10m of a watercourse. There must be no other application of nutrients as fertilisers, other organic manures or waste materials (including sewage sludge). Ploughing, sub-surface cultivation and modifications to the existing drainage system are not permitted, except as part of a sward enhancement plan agreed with your Adviser. [This includes subsoiling and mole ploughing.]’

The application of FYM to cultivated as opposed to grassland is deemed to be the most effective strategy to maximise the contribution of FYM to the accumulation of SOC$^{14}$. On permanent grassland management conducive to the accumulation of SOC is already present (the SOC was assumed to be at its maximum at equilibrium). It would be preferable therefore to specify the application of FYM to cultivated land as opposed to grassland where possible. Any restriction on the timing of the application of manures during the spring (for example to prevent damage to ground nesting bird sites) also reduces the window in which the N available from manures (and potential to substitute inorganic N) is at its maximum$^{39}$. The N requirement could be supplied by clover if there is no clash with the desired species mix (eg semi-natural species rich grassland maximum 25 - 30% clover). The use of clover within grassland has been recommended as a means to mitigate GHG emissions and is becoming increasingly popular$^{15}$. 

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Further, the use of clover in grassland has shown a positive adaptive response to predicted increases in spring temperatures due to climate change. It is forecast that upland beef and sheep farms may increase in total production by between 10 and 25%, with a combination of grass and white clover compared to pure grass fertilised with 100 kg N ha⁻¹. There would not therefore be income foregone associated with the use of clover within grassland. The application of N to grassland that may be water-logged and where anaerobic conditions prevail during part of the year are at greater risk to increased emissions of N₂O from soil. This may be applicable to option EK4 (Management of rush pastures (outside the LFA)) and further restrictions on the quantity of inorganic N (assuming that N from manures is applied to cultivated land where possible) would be preferable. For example, options EL5 (Enclosed rough grazing (LFA land)) and EL6 (Moorland and rough grazing) state ‘do not apply fertiliser, manure, lime or slag’.

Other examples where there are restrictions on fertiliser and pesticide inputs include:

a) Maintenance of traditional orchards in production (HC19): ‘Farmyard manure and/or inorganic fertiliser may be applied where soil tests show a nutrient deficiency and with written consent from your Defra adviser’. There must be no [other] application of nutrients such as fertilisers, [other] organic manures or waste materials (including sewage sludge). Pesticides and fungicides may be applied to orchard fruit trees to control specific pests and diseases. Their use is limited to specific situations and chemicals [detailed in the technical guidance / agreed in writing with your Defra adviser]’. It is also preferable to apply the FYM to cultivated land as opposed to land where there is infrequent tillage such as an orchard in order to maximise the potential contribution to the accumulation of SOC.

4.8. An initial increase (one year only) in CO₂e emissions where there was a reduction of the AGC through non-cropping or scrub removal or SOC due to the increased frequency in the cultivation of improved (ploughed and re-seeded) grassland. In general this initial increase was nullified post year one through permanent CO₂e savingsₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑ廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨廨�
unconstrained by GHG mitigation objectives, resulting in no net reduction of emissions\textsuperscript{17} or a potential increase in the form of, for example, greater transportation distances and fuel consumption. A review of the life-cycle analyses for the UK post-farm gate and non-UK pre and post-farm gate of a variety of commodities has already been conducted\textsuperscript{86} although the study highlighted numerous gaps in the data, different methods used in the analysis and/or differences in system boundaries. This prevented a direct ‘like for like’ comparison between UK and overseas produce to be made. The UK does not import large quantities of liquid milk as it is around 90% self-sufficient\textsuperscript{93} although the current unfavourable economic situation of dairy production has resulted in reduced levels of production. The implementation of ES options on improved grassland grazed by dairy cattle whereby dairy output is reduced is therefore unlikely to have an impact since the reduction is already occurring. In contrast the UK production of beef increased by 7.2% in 2005, to 763,000 tonnes, 74% of total consumption\textsuperscript{84}. The total imported from the EU (mainly Ireland) was 208,000 t and from non-EU sources (mainly Australia, Brazil and Argentina) 78,000 t. It is also forecast that the current trend towards increased UK consumption is likely to continue\textsuperscript{84}. The UK production of lamb and mutton was 321,000 tonnes in 2005, around 87% of the total consumed, 21,000 t were imported from the EU and 113,000 t from outside the EU, (mainly New Zealand), the greatest non-EU import volume for the meat sector as a whole\textsuperscript{84}. The trend in lamb consumption is also forecast to increase. Any potential increase in imports as a result of significant reduction in beef and lamb production through the implementation of ES therefore requires consideration. The globally growing demand for meat has been forecast to result in further changes in land use (such as forestland to grassland) and an increased demand for animal feeds (such as cereals)\textsuperscript{17}. The increased transportation distance (‘air miles’) in particular by air freight from countries such as New Zealand and South America risks the elimination of any C savings\textsuperscript{86} that may arise from those ES options on improved grassland should they result in increased imports. The GHG mitigation of ES agricultural land will be maximised through minimising the GHG emissions per tonne of yield and this will also reduce the risk of the displacement of production outside of the UK. Methods to mitigate agricultural GHG emissions that do not impact upon yield or that are likely to enhance it have been reviewed\textsuperscript{82} and the current calculations of the GHG balance\textsuperscript{86} of ES options include or make reference to these methods where applicable. Several of these methods (for example optimal timing of manures to maximise the available N to the crop and only supplying the crop requirements) fall within the remit of the revised NVZs Action Programme, others within Good Agricultural Practice. It is also probable that an increase in the efficiency of production will reduce production costs, particularly in light of a recent significant increase in the price of fertilisers. Income foregone therefore is unlikely and there will be no need to compensate the farmer through ES payments.

4.10. Previous studies have identified the largest C sequestration and reduction in GHG emissions to result from an increase in the proportion of permanent woodland, biomass energy crops (short rotation coppice (SRC) or Miscanthus) with further significant contributions on arable land from a greater use of permanent conservation field margins\textsuperscript{1,2,13,14,15}. Options to establish permanent woodland on arable land or improved grassland were not considered due to their implementation via schemes administered by the Forestry Commission and energy crops through alternative Defra schemes. The options within ES that are generally available and that have the greatest potential to reduce the GHG balance\textsuperscript{86} of land were the grass buffer strips. As discussed in paragraph 4.3 there is little scope to reduce the GHG balance\textsuperscript{86} of these options further since current inputs are practically zero. The maximum width of grass strips supported within ELS schemes is currently 6 m. Encouragement to enter a greater area of land as grass buffer strips may be possible through an increase in the maximum width of strips permissible that, per ha of option, will allow implementation along a smaller boundary length and on fewer fields. In order to avoid the displacement of production outside of the UK as discussed in the previous paragraph mitigation strategies within agricultural land require focus upon maximising the reduction in GHG emissions per unit of output. A review of such practices has already been undertaken\textsuperscript{82}. A key strategy is an improvement in the application of N through temporal and spatial targeted applications of inorganic fertiliser or improved timing of manures to maximise the N available to the crop\textsuperscript{39,82}. Many ES options currently reduce or eliminate N fertiliser and have a significant associated decrease in GHG emissions\textsuperscript{86} relative to the baseline scenario but at a cost of a loss in production. The efficiency of fertiliser is maximised by application of the economic optimum\textsuperscript{82} that may be hindered by within field spatial variation in soil type. The following are suggested for consideration do not incur a loss of yield (thus reduce the risk of displaced production i.e. increased imports) but will decrease GHG emissions associated with fertiliser use:

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1. *Encourage Fertiliser and Advisors Certification and Training Scheme (FACTS) membership.* Defra project report AC0206\(^{62}\) highlights two key strategies to reduce N fertiliser use while maintaining production: (1) not to exceed crop N requirements and (2) to make full use of the manure N supply allowance. For both strategies the report recommends that farmers should obtain qualification with the Fertiliser and Advisors Certification and Training Scheme (FACTS) as a means of implementation and consideration to incentivise this through ES is further recommended for consideration. Costs would include certification and the farmer’s time for training and the attendance of workshops etc annually to maintain certification. The potential reduction in fertiliser inputs will have an associated reduction in costs while no income foregone will result from a loss in yield.

2. *Encourage precision farming.* The accuracy of fertiliser (also herbicide, fungicide and growth regulator) application may be improved and thus the quantities applied decreased through precision farming and the use of in field sensors to modify application rates depending upon within field variations in, for example, soil type. Precision farming incurs a high initial cost from the purchase of equipment and would only be viable on larger farms. For example, yield improvements and fertiliser savings are estimated to provide a 133% return on any initial outlay within five years for a 500 ha farm. For the majority of farmers the cost is too great. The use of contractors and the spread of costs over multiple farms could be a potential route if demand was sufficient although at present an insufficient number of contractors are predicted to hinder widespread uptake\(^5\). The support of precision farming via a contractor by ES could potentially increase demand and thus contractor availability. Income foregone would be solely from contractor costs however such costs will be partially offset by potential improvements in yield and reduced input costs. *not included as part of the peer review process*

4.11. The current study has estimated the potential GHG mitigation\(^{EDP}\) properties of each option over the given time periods assuming there was no reversion to other management during this time although in reality this may be difficult to implement unless long term agreements are undertaken. Although temporary in nature C sequestration has been concluded to be a measure that may be implemented quickly and at minimal cost as an interim measure until more permanent measures become available\(^6\). Much of the C sequestration potential within Europe while predicted as being high is forecast to remain negligible as a contributor to GHG mitigation\(^{EDP}\) on account of high transaction costs\(^7\). The reimbursement of farmers through ES offers potential to overcome this barrier within England. There is a finite period of time over which C sequestration occurs after a change in the cultivation regime on arable land and this again is subject to an element of uncertainty with equilibrium established over a predicted 10\(^{15}\) or 50 – 100\(^{12}\) year timescale. The options at their current levels of uptake are predicted to peak in their climate change mitigation\(^{EDP}\) potential as a reduction of a proportion of annual UK GHG emissions\(^{EDP}\) after between 5 and 50 years. The 5 year period is compatible with the Kyoto accounting period. No further decrease will occur after this time on account of the SOC sequestered in options that create for example, semi-improved grassland on arable land (equilibrium established after 45 years) or unimproved grassland or grass strips on improved grassland (39 years) remaining constant. The annual reduction in net CO\(_2\)e emissions\(^{EDP}\) due to sequestration is assumed to be constant each year until the equilibrium has been reached. The reduction in the proportion of total UK GHG emissions\(^{EDP}\) declines as the options continue to reduce permanent emissions from reduced inputs but not the temporary CO\(_2\)e savings\(^{EDP}\) from sequestration. Post year 50 this becomes more apparent due to no further SOC accumulation in options that create unimproved grassland or grass strips on arable land (55 years) or AGC accumulation in the form of tree growth. The options do however maintain a C store and reversion to the original form of land management would see the C sequestered for each land use scenario returned to its original levels and atmospheric emissions increase. Environmental Stewardship makes an important contribution to the preservation and restoration of peat soils where large quantities of C are stored. To maximise the C sequestration potential of options within ES the habitat maintenance, restoration and creation options should preferably be offered for longer-terms than the 5 and 10 years currently within ELS and HLS agreements respectively.

4.12. Should land be returned to its original use then the options with the greatest permanent CO\(_2\)e savings\(^{EDP}\) will make the largest contribution to a reduction in the UK GHG emissions\(^{EDP}\). Again these are the options with virtually zero inputs, the grass buffer strips or similar. They do however also remove land from production and risk the displacement of production outside
of the UK and the study would benefit from accounting for this impact once the results of Defra Project FO0103\(^8\) become available. In order to minimise the risk of any displacement of production it is necessary to support management strategies that maximise the efficient use of inputs and minimise emissions but do not compromise on yield such that an increase of imported agricultural commodities becomes necessary. There are other key strategies within the production cycle where the potential for to reduce GHG emissions may be considerable, for example a reduction of CH\(_4\) from enteric fermentation through the manipulation of diet, or a reduction in inorganic fertiliser N through the adoption of increased N efficient varieties\(^8\). At present such techniques are under development but may be worthy of consideration in the future. More wide scale adoption of such technologies could be promoted via ES should an additional financial cost to the farmer be incurred through their use.
This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.


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