Natural England Commissioned Report NECR121

# Measuring the extent to which greenhouse gas emission savings achieved by Environmental Stewardship are displaced on-farm

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# Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

## Background

Climate change is a long-term challenge that potentially affects all parts of the Earth. The mitigation of Green House Gases (GHG) emissions is a key climate objective for society to tackle, and one in which rural areas, businesses and communities have a role.

Environmental Stewardship (ES) provides funding to farmers and other land managers in England to deliver effective environmental management on their land. Many of the available options offer opportunities for mitigating the effects of climate change either by reducing greenhouse gas emissions or by increasing carbon sequestration on the land under the option.

However, there is no information on what effect putting land under these options has on crop yields or on the remaining land not under the options. For example: does uptake of the maize management options impact on maize yields; where an ES option requires that land be taken out of production, is there an increase in GHG emissions on land not covered by ES options, reducing or negating the benefits of implementing the Environmental Stewardship options?

This work was commissioned to investigate:

- how farmers respond to implementing the Environmental Stewardship options that are most effective at reducing GHG emissions (priority options);
- what impact these options have on on-farm crop yields and livestock numbers; and
- what are the potential for emissions displacement.

The project involved a series of interviews with ES agreement holders designed to identify how their uptake of ES management requirements had impacted on inputs and yields and the results will be used to help inform the implementation, targeting and development of Environmental Stewardship and other future agri-environment schemes.

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**Further information**
This report can be downloaded from the Natural England website: **www.naturalengland.org.uk**. For information on Natural England publications contact the Natural England Enquiry Service on 0845 600 3078 or e-mail **enquiries@naturalengland.org.uk**.

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# Measuring the extent to which greenhouse gas emission savings achieved by Environmental Stewardship are displaced on-farm

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## Report Preparation:

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## Executive summary

Climate change is a long-term challenge that potentially affects all parts of the Earth. Human activities make a significant contribution to increased concentrations of greenhouse gases (GHGs) in the atmosphere, and this impacts on climate. The mitigation of GHG emissions is a key climate objective for society to tackle, and one in which rural areas, businesses and communities have a role. Environmental Stewardship is an agri-environment scheme that provides funding to farmers and other land managers in England to deliver effective environmental management on their land. Many of the available options offer opportunities for mitigating the effects of climate change either by reducing greenhouse gas emissions or by increasing carbon sequestration. The following study investigates how farmers respond to the uptake of those options most effective at reducing GHG emissions (priority options) and the impact these options have on on-farm crop yields and livestock numbers, and the potential for emissions displacement.

No impact on crop yield was stated by farm managers for options EJ2 (Management of maize crops to reduce soil erosion) and HD3 (Low depth, non-inversion cultivation on archaeological features). The undersowing of spring cereals (EG1 / OG1) experienced yield reductions depending on whether an existing spring sown crop was substituted or, more crucially, whether a winter sown cereal was replaced with a spring cereal. Prolonged absence of precipitation between February and April in the south-east of England reduced the yield of spring sown cereals relative to winter cereals, and increased greenhouse gas emissions per unit of output. Earlier maize harvest followed by a winter as opposed to a spring cereal improved crop yields overall, especially when precipitation during the spring was below average and spring cereals incurred heavier stated yield penalties. Emissions reductions in EJ2 / EG1 / OG1 increased with establishment of an undersown grass / clover mixture, coupled with mitigation of surface run-off on steeper gradients with higher soil organic carbon content. Field specific variables such as slope aspect were stated to cause poor establishment of the undersown crop and the mitigation potential of the option overall, although this was limited to only one case study.

Options that remove a proportion of a field from agricultural production (grass buffer strips, within field grass areas, beetle banks) reduced emissions in response to baseline soil organic carbon, soil texture and within field slope gradient, in addition to emissions associated with agricultural production (agro-chemicals and field operations). No on-farm displacement as a result of these options was evident. The actual reduction in crop yield depended on the location of the option relative to field specific factors such as woodland, hedgerows and watercourses, and management techniques applicable to LERAPS assessments (for example spray application method, type of crop protection product). Strips to the north of woodland were stated to be sufficiently shaded as to not yield, while crop yields were typically lower where specific crop protection products

were prohibited. Full yield reduction was experienced where options were located in central field areas.

Potential on-farm displacement arose where the restoration of moorland (HL8 / HL10) relocated livestock onto formerly unimproved grassland below the moorland line. The associated increase in emissions from conversion to semi-improved grassland was lower than the predicted decrease in $CO_2$ from soils due to the restoration programme. A net decrease in emissions resulted although an associated risk of topsoil compaction in the formerly unimproved grassland was potentially an issue. The utilisation of peripheral farm areas and the small parcel sizes meant that the habitat creation options HC9 (Creation of woodland in Severely Disadvantaged Areas) and HC17 (Creation of successional areas and scrub) had a negligible impact on farm yields. No on-farm displacement was stated for either option.

In summary, most options for the case study farms assessed did not cause on-farm displacement of production or alter management outside the option boundaries. The GHG mitigation potential of options that maintain agricultural production are maximised where yield reduction is also minimised. For option EJ2 the undersowing of the crop, followed by a winter cereal achieves this objective, potentially facilitated by the use of earlier maturing maize varieties, especially at higher altitudes or with progression north. Options that replace winter cereals with undersown spring cereals appear to be more vulnerable to greater yield reduction and increased GHG emissions per unit of output where there is a greater risk of prolonged below average spring rainfall, and lower available soil water (for example on coarse soils). Areas of south-east England for example may be particularly vulnerable, and taking this risk into account when implementing these options would be advisable. Options that remove a proportion of a field from production potentially maximise GHG mitigation with appropriate positioning (for example where there is surface run-off) or where yield reduction may be lower (adjacent to / north of woodlands, adjacent to watercourses, areas of poor drainage). Where restoration of moorland habitats occurs on degraded carbon rich soils, a displacement of livestock onto mineral soils of lower SOC, subject to available land and adherence to recommendations, would be potentially beneficial assuming $CO_2$ emissions from the degraded baseline soils are then mitigated.

## 1.0. Introduction

Climate change is a long-term challenge that potentially affects all parts of the Earth. Human activities make a significant contribution to increased concentrations of greenhouse gases (GHGs) in the atmosphere, which in turn impacts upon climate. Consequently there are two key climate objectives for society to tackle, firstly to mitigate GHG emissions (to reduce atmospheric concentrations and limit the severity of any future changes in climate), and secondly to adapt to the changes that do arise and ensure that the ecosystem services upon which society rely are sustained. Rural areas, businesses and communities have their role to play with regard to these objectives.

Environmental Stewardship (ES) is an agri-environment scheme that provides funding to farmers and other land managers in England to deliver effective environmental management on their land. The scheme is a part of the Rural Development Programme for England (RDPE) which implements the EU Rural Development Regulation (RDR) and Pillar 2 of the Common Agricultural Policy (CAP). The Programme is jointly funded by the EU through the European Agricultural Fund for Rural Development (EAFRD) and the UK Government. Environmental Stewardship is open to all farmers and land managers across England, providing farmers and land managers with a financial incentive that supports and rewards them, through voluntary management agreements, for looking after England's countryside and its wildlife, landscapes, historic features and natural resources (soils and water) and for providing new opportunities for public access. Applicants for an ES agreement select specific management activities from a wide range of available options. In Entry Level Stewardship (ELS) / Organic Entry Level Stewardship (OELS) each option carries a points score and a minimum total score must be achieved to attain scheme eligibility. In HLS options are selected in discussion with Natural England advisers. Higher Level Stewardship (HLS) is targeted to address priority land management objectives. Many of the available options offer opportunities for mitigating the effects of climate change either by reducing greenhouse gas emissions or by increasing carbon sequestration.

Natural England have required a study to be undertaken to investigate how farmers respond to the uptake of options that reduce GHG emissions through a reduction of inputs. Research questions include:

- Do farmers intensify elsewhere on their farm or improve the efficiency of their input use?
- Does uptake of these options cause a noticeable reduction in production levels, giving rise to the potential for emissions displacement?

Emissions displacement may result when a reduction in GHG emissions achieved through participation in ES (eg decreased emissions due to ceasing nitrogen fertiliser input), leads to a loss of farm production within the area managed under ES, which is then compensated for by an increase in production and inputs in areas of the farm (either on the same farm or another farm) outside of the ES area, resulting in increased GHG emissions. The following report presents the findings to these questions.

## 2.0. Aims and Objectives

From the tender:

1. *Provide an estimate of the nature, and scale, of displacement of GHG emissions following ES participation.*
2. *Provide recommendations for reducing the level of displacement.*

## 3.0. Methodology

### 3.1. Case study regions and baseline data

Farms from Kent (south east England) and Northumberland (north east England) have been chosen in order to represent diversity of climate, topography, altitude and baseline soil conditions. The baseline regional conditions have been derived from the European Commission Joint Research Centre (JRC) GIS data-sets and from data within the ARCGIS® software. The datasets are summarised in Table 3.1 with the case study region mapped spatial distributions in Figures 3.1 and 3.2. In order to preserve confidentiality, the case study farms have not been marked on the maps. Their baseline characteristics are summarised in Table 3.2.

Table 3.1. Summary of GIS data-sets (1 $km^2$ resolution unless stated otherwise).

| Description | Source |
|---|---|
| Annual and seasonal rainfall (30 year average) | EDIT - Toward the European Distributed Institute of Taxonomy |
| Annual evapotranspiration (30 year average) | EDIT - Toward the European Distributed Institute of Taxonomy |
| Elevation | ArcGIS® Geographical Information Software (100 $m^2$ resolution) |
| Slope gradient | ArcGIS® Geographical Information Software (100 $m^2$ resolution) |
| Slope aspect | ArcGIS® Geographical Information Software (100 $m^2$ resolution) |
| Land cover: CORINE | CORINE Land Cover 2006 raster data - version 16 (04/2012): 2000 and 2006 combined. European Environment Agency |
| Soil: Pan-European Soil Erosion Risk Assessment (PESERA) | PESERA: European Commission Fifth Framework Programme (2002). Contract QLK5-CT-1999-01323. Joint Research Centre European Soil Portal and Kirkby *et al*. (2004) |
| Soil: Natural Susceptibility to Soil Compaction | Soil Data and Information Systems. Natural susceptibility to compaction. Joint Research Centre European Soil Portal and Houšková and Montanarella (2007) |
| Soil: Soil organic matter content | Soil Data and Information Systems. Map of Organic Carbon Content In Topsoils In Europe: Version 1.2 September - 2003 (S.P.I.04.72). Joint Research Centre European Soil Portal and Jones *et al*. (2005) |
| Soil: Dominant soil texture | European Soil Database V 2.0 Raster Library 1 km x 1 km Dominant surface textural class. Joint Research Centre European Soil Portal and Panagos *et al*. (2012) |

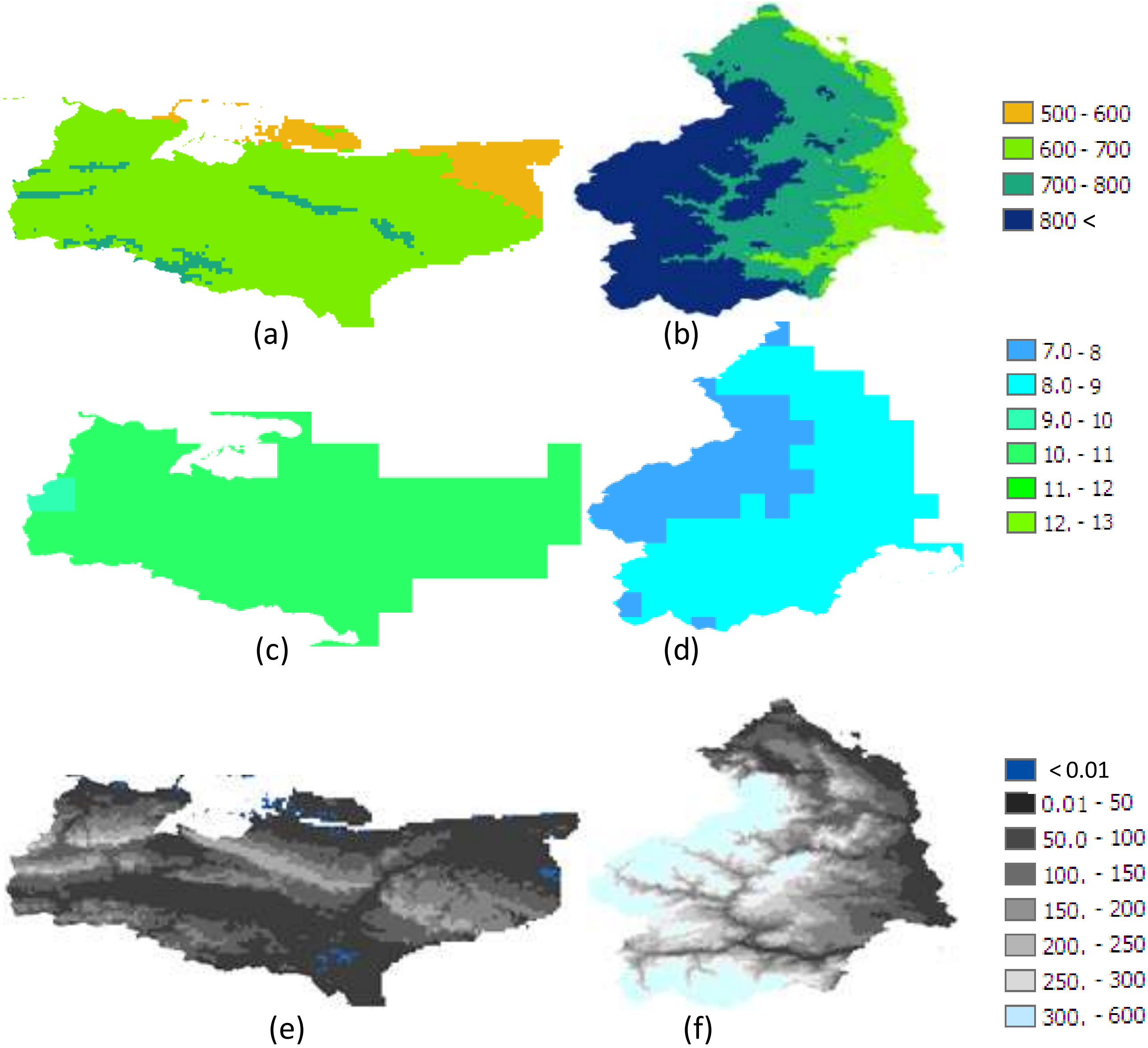


Figure 3.1. Climatic variables: (a & b) mean annual rainfall (mm) and (c & d) annual temperature (°C); (e & f) altitude in Kent and Northumberland respectively.

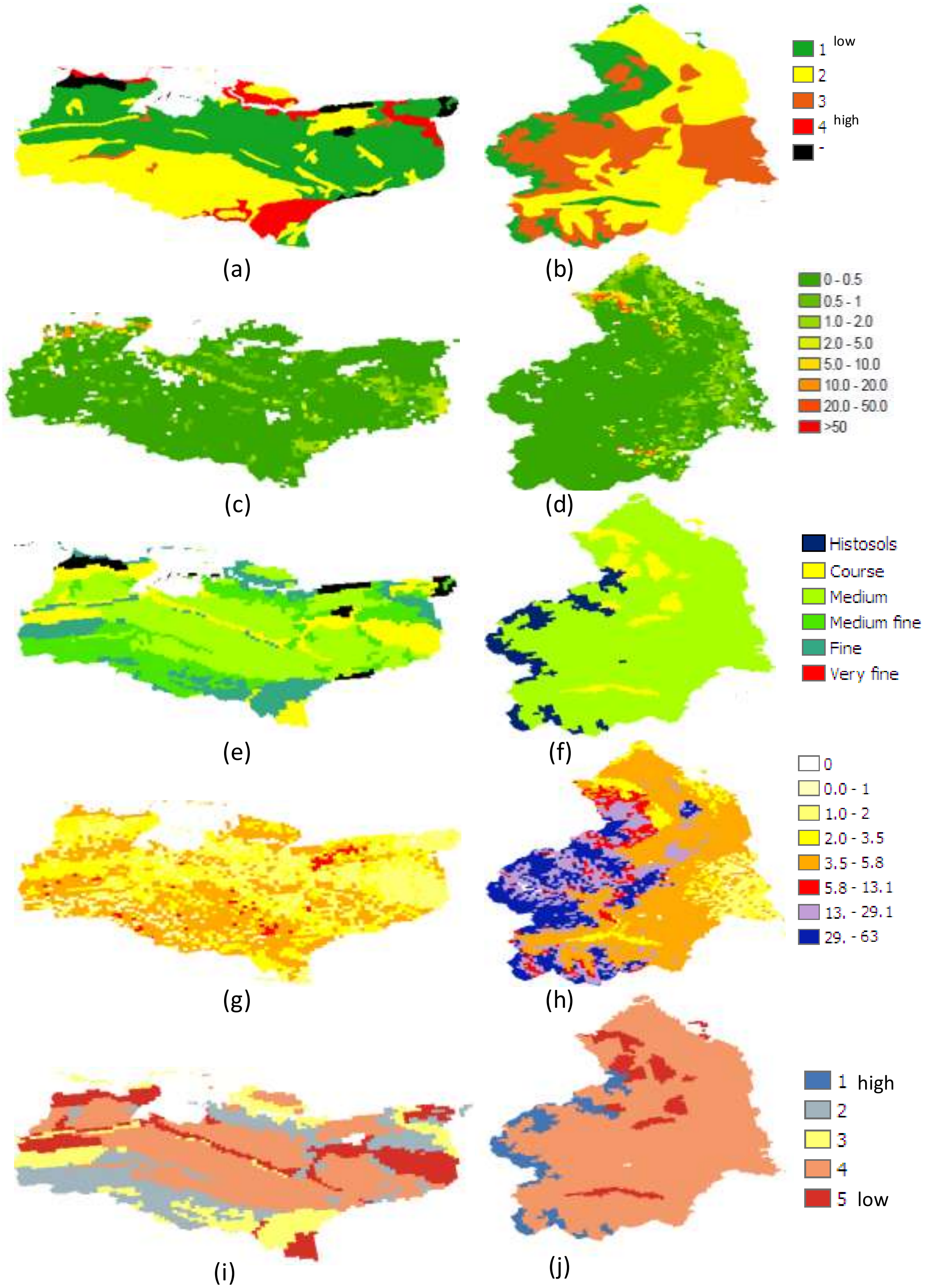


Figure 3.2. Baseline soil variables: (a & b) natural susceptibility of soil to compaction; (c & d) PESERA risk of soil erosion; (e & f) dominant soil texture; (g & h) percent soil organic carbon (i & j) available soil water capacity in Kent and Northumberland respectively.

## 3.2. Farm-based case studies and data collection

From the Tender: *'Natural England and the contractor will agree priority options (based on Natural England Technical Information Note 107, Tables 1 and 2) and a selection of potential ES agreements to be used as case study sites (the exact list of options will depend on their availability at selected study farms)'*. The selected priority options from Natural England Technical Information Note TIN107 (Natural England, 2012) are summarised in Table 3.2.

Table 3.2. Priority Environmental Stewardship options.

| Code | Option |
|---|---|
| **Assumption of no displacement** | |
| EG1 | Under sown spring cereals |
| EJ2 | Management of maize crops to reduce soil erosion |
| HD3 | Low depth, non-inversion cultivation on archaeological features |
| OG1 / OHG1 | Under sown spring cereals on organic land |
| | |
| **Options that remove part of a field from production (to gauge the extent of displacement)** | |
| EE3 | 6m buffer strips on cultivated land |
| EE9 | 6m buffer strips on cultivated land next to a watercourse |
| EE10 | 6m buffer strips on intensive grassland next to a watercourse |
| HE10 | Floristically enhanced grass margin |
| HF7 | Beetle banks |
| HJ5 | In-field grass areas to prevent erosion or run-off |
| HK7 | Restoration of species-rich, semi-natural grassland |
| HL10 | Restoration of moorland |
| HL8 | Restoration of rough grazing for birds |
| | |
| **Habitat creation options (to gauge the scale of displacement)** | |
| HC9 | Creation of woodland in Severely Disadvantaged Areas |
| HC17 | Creation of successional areas and scrub |

### 3.2.1. Field specific physical baseline data

The case study farms were selected for the presence of priority options listed in Table 3.2. The ES agreement farm map, marked with the exact location of fields registered on the Rural Land Registry (land parcels registered for compliance with the Rural Payments Agency and eligible for entry into Environmental Stewardship) within each farm case study and the priority ES options of interest were digitised within the Geographical Information System (GIS) software ArcGIS® and overlaid onto the soil and climate data-sets described in section 3.1. Local site topography (gradient and aspect of slope) and the presence of local features such as watercourses were obtained from ArcGIS® and used in the formulation of the field specific baseline scenarios. The process is summarised in Figure 3.3. The formulated case study baselines are summarised in Table 3.3. The location of individual Environmental Stewardship options have been added to each individual field as relevant using the digitised field boundaries. This allows the creation of field specific ES option scenarios and impact calculations (section 3.3).

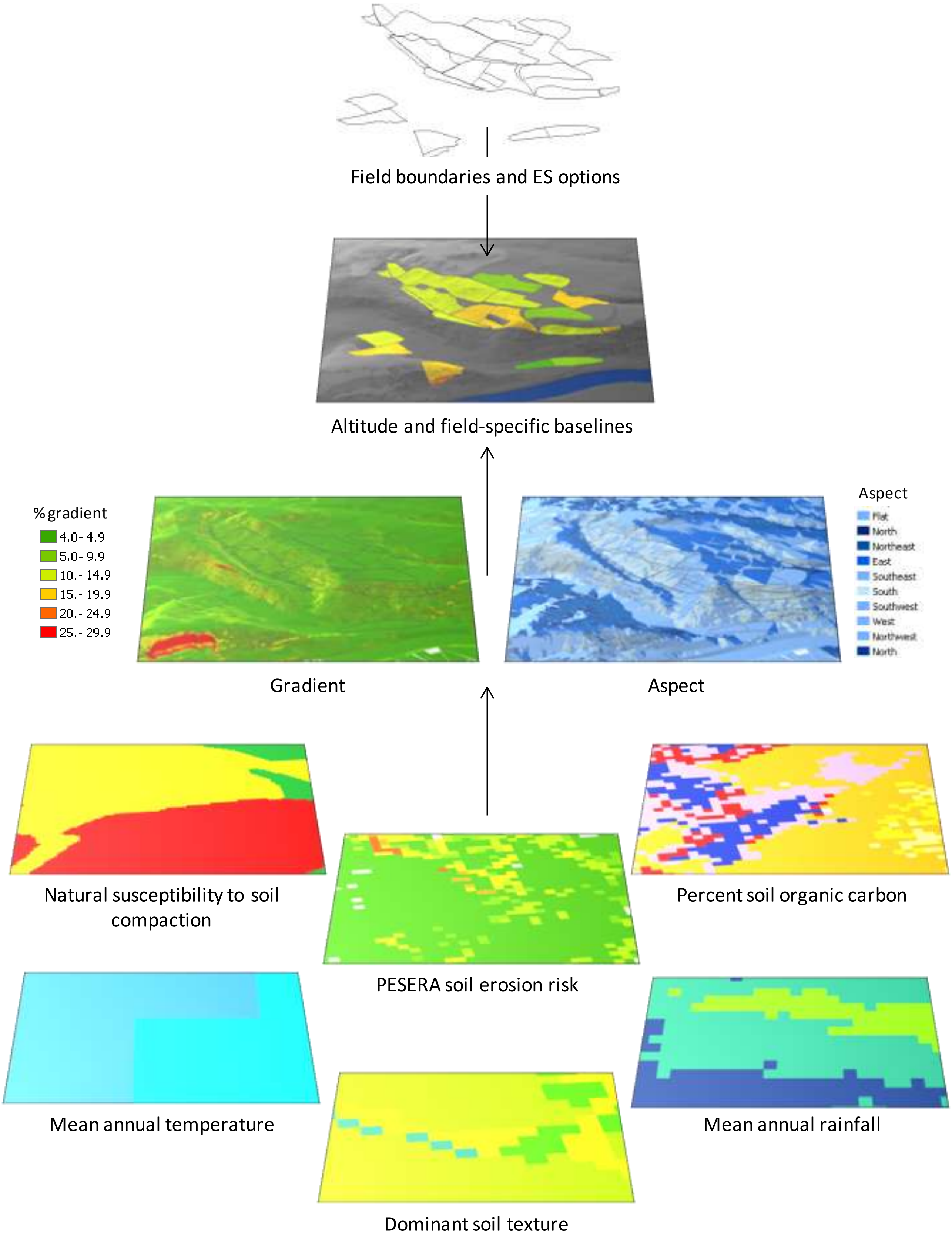


Figure 3.3. The creation of baseline case study farm scenarios with GIS datasets. Note: for illustrative purposes only.

Table 3.3. Summary of case study farm baselines.

| Case study | Mean annual rainfall (mm) | Mean annual temp (°C) | Soil texture | %SOC | NSS compact$^{n}$ | Soil erosion (t soil ha$^{-1}$ yr$^{-1}$) | Altitude (m) | Max field gradient (°) | Priority options |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 600-700 | 10-11 | Course; medium | 0.99-1; 3.5-5.8 | 1 | 0–0.5; 2.0–5.0 | 50-100 | 16 | OG1/OHG1; EF1 |
| **2** | 600-700 | 10-11 | Medium | 2.0-3.5; 3.5-5.8 | 2 | 0–0.5 | 0-50 | 8 | EJ2; EE4,6; EE10 |
| **3** | 600-700 | 10-11 | Fine | 3.5-5.8 | 2 | 0–0.5 | 50-150 | 23 | HK7, OHG1 |
| **4** | 600-700 | 10-11 | Medium | 1.0-2.0; 2.0-3.5 | 1, 2 | 0–0.5 | 0-100 | 9 | EJ2; EE3; EF1 |
| **5** | 600-800 | 10-11 | Course | 2.0-3.5; 3.5-5.8 | 1, 2 | 0–0.5 | 150-250 | 26 | EJ2; EE2,9; EF1 |
| **6** | 600-700 | 10-11 | Fine | 2.0-3.5 | 4 | 0–0.5 | 0-50 | 6 | EJ2; EE3 |
| **7** | 600-700 | 10-11 | Course; medium | 0.99-1; 1.0-2.0 | 1 | 0–0.5 | 0-150 | 23 | EE3, min till |
| **8** | >800mm | 8-9 | *Medium* | 3.5-5.8; 13.1-29.1 | 2, 3 | 0–0.5 | 150-300 | 40 | EE3 |
| **9** | >800mm | 8-9 | *Medium* | 3.5-5.8; 13.1-29.1; 29.1-63 | 2, 3 | 0–0.5 | 200-300 | 20 | HL10 |
| **10** | >800mm | 8-9 | *Medium* | 3.5-5.8; 13.1-29.1; 29.1-63 | 2, 3 | 0–0.5 | 150-300 | 24 | HL10 |
| **11** | >800mm | 7-8; 8-9 | *Medium* | 13.1-29.1; 29.1-63 | 3 | 0–0.5 | 200-300 | 19 | HK7 |
| **12** | >800mm | 8-9 | *Medium* | 3.5-5.8; 13.1-29.1; 29.1-63 | 2 | 0–0.5 | 150-200 | 34 | HC9; HE10 |
| **13** | >800mm | 8-9 | *Medium* | 3.5-5.8; 5.8-13.1; 13.1-29.1; 29.1-63 | 2, 3 | 0–0.5 | 200-300 | 33 | HL10 |
| **14** | >800mm | 8-9 | *Medium* | 3.5-5.8; 13.1-29.1 | 2, 3 | 0–0.5 | 150-300 | 39 | EE3,9; HC9,17; HD3; HE10,HF7; HJ5 |
| **15** | >800mm | 8-9 | *Medium* | 2.0-3.5; 3.5-5.8; 5.8-13.1; 13.1-29.1 | 1, 2 | 0–0.5 | 150-300 | 42 | OHG1 |

### 3.2.2. Farm specific case studies and baseline management scenarios

A baseline management scenario is required in order to provide a reference point against which any changes in land use through the implementation of ES agreements may be compared with its existing use and the net increase or decrease in GHG emissions quantified. A management scenario states all processes involved with the growing of the crop to include application of crop protection products (product, active ingredient and application rate ha$^{-1}$), fertilisers (product, nutrient composition and rate ha$^{-1}$), field operations (type of implement, depth of operation and frequency) livestock (type, rates and grazing period), management of manures, addition of organic amendments (farmyard manure, incorporation of crop residues) (Defra, 2003; Lewis *et al*., 2010; Tzilivakis *et al*., 2005ab; Warner *et al*., 2008, 2010, 2011b). It also takes account of environmental factors such as soil type and rainfall that may impact on loss of N to de-nitrification and thus $N_2O$ emissions.

Farm specific baseline management scenarios have been formulated, as far as possible, at the individual field scale, in response to the interviews with selected land managers and baseline GIS data-sets. Farm management data where applicable to fields containing priority ES options listed in Table 3.2 were sourced in liaison with selected agreement holders supplied by Natural England Officers to include, on a field by field basis as relevant and in reference to the farm maps and avalable farm records, the following layers of detail (1 to 4 in ascending level of detail) as used previously by Warner *et al*. (2011a) when undertaking interviews with farm managers. They have been used to formulate original management (pre-option) and current management (post option) to identify changes in farm inputs and outputs related to the uptake of selected priority ES options:

1. General management practices (yes or no) (e.g. application of NPK, organic manures, use of particular type of machinery, herbicides), difference in management of improved and unimproved grassland.
2. Timing (when inputs are applied or stock grazed, crops sown, grassland reseeded) or duration (e.g. time since last reseed).
3. Stocking rates (livestock units per ha), depth of tillage on arable or reseeded grassland, seed mix.
4. Precise application rates (NPK, FYM, herbicides), dietary constituents of livestock and quantities per animal.

Where specific data was not available (for example level 4 data) standard crop recommendations (for example Defra, 2010) in reference to the specific farm case study climate and soil texture have been consulted. Requests were made to the land manger of any impact that uptake of priority options had on farm inputs within both the area covered by the option and additional areas of the farm where the option was not present but had influenced the inputs in either the same or another field as a means of compensation for yield reduction. Site topography (gradient of slope) and aspect (direction of slope) has been included within the assessment and derived and marked on farm maps using ArcGIS® software and overlaid onto the baseline soil data-sets described in section 3.2.1 (dominant soil texture, percent soil organic carbon, natural soil susceptibility to compaction (Houšková and Montanarella, 2007) and risk to soil erosion (Panagos *et al*., 2012). Where detail at the individual field level was not possible, aggregation of fields with identical land use and management has been undertaken.

Environmental Stewardship option management scenarios have been constructed for each case study farm in reference to data collected from land managers, the existing scenarios constructed for Defra Projects BD2302 and BD5007 (Warner *et al*., 2008; 2011b) and Natural England ES Handbooks (Natural England 2010ab, 2013) applied to local site topography and soil properties listed in section 3.2.1.

### 3.3. Farm scale ES option Life-cycle Assessment (LCA)

A farm scale greenhouse gas balance for the selected priority options present on chosen case study farms (Table 3.3) has been calculated, where 'whole farm' refers to the impact of the priority option across the whole farm to include all fields where the implementation of the option has caused a change in management on farm, if applicable.

A Life-cycle Assessment (LCA) approach has been used, drawing on existing work undertaken by Warner *et al*. (2008, 2011b) for Defra (projects BD2302 and BD5007) and for the European Commission (Lewis *et al*., 2010, 2012) is used to quantify the net GHG emissions, either positive or negative, under each ES option relative to the baseline land use for each farm case study. Life Cycle Assessment is an internationally standardised method for the evaluation of all the environmental impacts (both positive and negative) of a product (or a service) throughout its complete life cycle (ISO 14040-43) and has to date been successfully applied to agriculture and horticulture (Defra, 2003; Tzilivakis *et al*., 2005ab; Warner *et al*., 2008, 2010, 2011b). For the purpose of this project the LCA would focus solely on greenhouse gases however the principles of the analysis will be applied. The alterations in land management associated with each ES option will have firstly, a direct impact on the processes that affect GHG emissions from within the immediate environment i.e. where the ES option is implemented (such as increased emissions of $N_2O$ from the soil). Secondly, they will also have indirect impacts through, for example, the reduction or prohibition of the use of certain agro-chemical products. Each product has GHG emissions (namely $CO_2$ from the combustion of fossil fuels) associated with their manufacture, packaging and transport and these must also be taken into account. An LCA considers the impacts of the entire system and potential impacts throughout a product's life, where in this case the product is each ES option.

A typical LCA consists of the following steps:

1. Goal and Scope Definition: describes the application covered, the reasons for carrying out the study, and the target audience. The scope is the detailed technical description of the "product system" under study, in this case the baseline scenario and each ES option.
2. Life Cycle Inventory Analysis: consists of the compilation and quantification of the environmental inputs and outputs for the product system throughout its life cycle. It will include GHG emissions from the manufacture of any products applied, the manufacture of machinery used and the fuel consumed for field operations, changes

in $N_2O$ or $CH_4$ emissions and C sequestration associated with changes in land use and/or management through implementation of ES options.

3. Life Cycle Impact Assessment: to interpret and evaluate the magnitude and significance of the potential environmental impacts of the product system. For each option the overall GWP balance, including on-farm displacement, will be calculated and compared with that of the baseline scenario.
4. Interpretation: the conclusions and recommendations are derived from the findings of the life cycle inventory analysis and impact assessment in line with the defined goal and scope. The overall impact of ES options on GHG emissions within England based on national uptake per hectare (ha) and maximum potential impact with assumed optimal uptake of those options with the greatest GHG mitigating properties. Recommendations to encourage uptake of such options will be made.

### 3.3.1. $CO_2$ from fossil fuels

The combustion of fossil fuels emits GHG's, mainly $CO_2$ (Jackson *et al*., 2009). Within agricultural systems, fossil fuels power farm machinery to undertake soil tillage and agro-chemical application. Further up the supply chain, fossil fuels are used for the manufacture of agro-chemicals and farm machinery and for the transportation of such products to the farm. The fossil energy use associated with crop production is related to the number of on-farm operations and the quantity of agro-chemicals applied, which is in turn dependent on the crop grown or livestock grazing system (Defra, 2003; Tzilivakis *et al*., 2005ab; Williams *et al*., 2009).

The GHG emissions resulting from the combustion of fossil fuels during management of land under each ES option will be quantified from the following three areas (Lewis *et al*., 2010; Tzilivakis *et al*., 2005ab; Warner *et al*., 2008, 2010, 2011b; Williams *et al*., 2009):

1. product manufacture (pesticides and fertilisers), packaging and transport (to farm).
2. application by spraying or spreading or fuel consumed by tillage operations and drilling
3. indirect energy (fuel consumed during machinery manufacture and calculated based on depreciation per operation).

Spatial factors responsible for variability in $CO_2$ emissions from fuel consumption associated with deeper tillage (ploughing, subsoiling and power harrowing) include soil texture (Kalk and Hülsbergen*,* 1999; Williams *et al*., 2009). Shallow cultivations (for example spring toothed harrow or discs) do not vary significantly in response to soil type, although more than one pass may be required on heavier soils (fine soil textures). Shallower cultivation depths reduce fuel consumption (Kalk and Hülsbergen*,* 1999), particularly on finer particulate soils with greater percent clay content.

Table 3.4. Fuel consumption derived GHG emissions (t $CO_2$e $ha^{-1}$) from ploughing, subsoiling and power harrowing in response to dominant soil texture and depth.

| Dominant soil texture | Subsoil (7 legs) | Plough (20 cm) | Power harrow |
|---|---|---|---|
| Coarse; Histosols | 0.042 | 0.036 | 0.057 |
| Medium; Medium fine | 0.066 | 0.050 | 0.057 |
| Fine; Very fine | 0.106 | 0.099 | 0.091 |

Subsoiling penetrates deeper (>30cm) soil layers. Its use following crops such as maize may be necessary, particularly on soils vulnerable to compaction, due to access by heavy machinery during harvesting which may cause deeper (subsoil) compaction. Biomass accumulation and yield in subsequent crops may be enhanced, and vulnerability to drought reduced where compaction is removed since crop root movement is not so restricted within the upper soil profile (Houšková and Montanarella, 2007). Its removal also reduces the risk of prolonged anaerobic conditions where soils, subject to N fertiliser application, risk increased denitrification and emission of $N_2O$ (Machefert *et al*., 2002).

### 3.3.2. Nitrous oxide ($N_2O$)

Nitrous oxide is emitted from soils when nitrifying bacteria (e.g. *Nitrosomonas* and *Nitrobacter*) oxidise ammonium ($NH_4^+$) from decaying organic material to nitrate ($NO_3^-$) in the presence of oxygen, or during denitrification of $NO_3^-$ by denitrifying bacteria to mainly dinitrogen ($N_2$) in the absence of oxygen (Machefert *et al*., 2002). Nitrate is also removed and $N_2O$ emitted due to leaching when the soil water field capacity is exceeded and drainage proceeds (Smith *et al*., 1996). The denitrification and leaching pathways both proceed in response to excess $NO_3^-$ present in the soil that is not utilised by the crop. Nitrogen is necessary for crop growth however when available N exceeds crop requirements, the surplus is vulnerable to environmental loss (Machefert *et al*., 2002; Oenema *et al*., 2005; Smith and Conen 2004; Smith *et al*., 2008). The incorporation of plant biomass (e.g. crop residues) and the presence of legumes (e.g. clover) also have the potential to return N to the soil and, where not assimilated by the crop, form $N_2O$ (Abberton *et al*., 2008; Smith *et al*., 2008). The mitigation of soil erosion and surface run-off reduces the risk of $NO_3^-$ loss (IPCC, 2006) and indirect emissions of $N_2O$, the magnitude of which is dependent on the gradient of the slope, the dominant soil texture (section 3.3.2.2) and the presence of organic matter. Nitrous oxide is also released during the manufacture of nitrate fertiliser (Hensen *et al*., 2006; Brentrup and Palliere, 2008).

On grassland, N is applied as grazing deposition in addition to fertiliser. The quantity is dependent on the type of animal (cattle or sheep), stocking rate, the proportion of the year the animal remains outside and diet (Abberton *et al*., 2008; Moorby *et al*., 2007). Less intensive grazing systems result in a reduced rate of N $ha^{-1}$ applied as grazing deposition and the risk of overlap between urine patches. This results in decreased N leached, decreased risk of poaching and denitrification and a decline in emissions of $NH_3$ (ADAS, 2007). Avoidance of overgrazing and poaching helps prevent soil compaction (Houšková and Montanarella, 2007) and the risk of anaerobic soil conditions. Emissions from the handling and storage of livestock manures depends on the method of storage, how long it is stored and the content of the diet and efficiency with which the N is utilised (Abberton *et al*., 2008; Freibauer, 2003; Moorby *et al.*, 2007; Williams *et al*., 2009).

$N_2O$ emissions from arable crops have been calculated for BD2302 and BD5007 (Warner *et al*., 2008, 2011b) using the IPCC (2006) methodology supplemented with data provided by the nitrogen balance model SUNDIAL (Smith *et al*., 1995). Further calculations to assess the impact of surface run-off for variable soil surface gradients, have been undertaken and applied to the gradients established for the baseline scenarios for each case study farm.

#### *3.3.2.1. $N_2O$ from leaching*

Sandy soils are more vulnerable to N loss via leaching, a risk that is increase by higher annual precipitation, particularly during the winter when residual $NO_3$- within the soil may be removed, or during the early spring when supplementary N is applied to soils potentially at field capacity (Defra, 2010; Smith *et al*., 1996). Leaching has been calculated for different soil textures by modification of the default proportion of N removed via leaching ($FRAC_{LEACH}$) on cultivated land (0.3 kg per kg of N applied) (IPCC, 2006), of which 0.75% forms $N_2O$ as indirect emissions (IPCC, 2006). Emission factors per kg N applied for nitrate leaching on three soil types (sand, loam and clay) and within three annual rainfall classes (<600 mm, 600-700 mm, >700 mm) have been derived by simulations with the N balance model SUNDIAL (Smith *et al*., 1996) for a winter wheat crop with N recommendations consistent with those provided by Defra (2010). Nitrate leaching may be reduced by winter cover crops (Silgram and Harrison, 1998), the impact of which on indirect $N_2O$ emissions from leaching depends on the soil susceptibility to leaching. Leaching risk correlates with soil texture and precipitation (higher risk on sand soils coupled with high rainfall) and residual soil N (increased risk where high N demanding crops were present previously and the soil nitrogen supply index is higher). Spring sown crops increase leaching vulnerability due to absence of a crop during the preceding winter (Silgram and Harrison, 1998). Winter cover crops, available within ES as an option targeted at high risk sandy soils (Natural England, 2010a), reduce residual soil N during this period before drilling of a spring sown crop when the soil would otherwise be fallow. The undersowing of maize as an option within option EJ2 (Management of maize to prevent soil erosion) also provides an opportunity for a winter cover crop if the subsequent crop is, for example, a spring sown cereal.

#### *3.3.2.1. $N_2O$ from nitrification and denitrification*

The fraction of N released during nitrification and denitrification that forms $N_2O$ is described by De Vries *et al*. (2003) as 0.0125 and 0.035 respectively on mineral soils. It quantifies the proportion of N from nitrification and denitrification generated by SUNDIAL, that is emitted as $N_2O$. On peat soils De Vries *et al*. (2003) specify a mean fraction of 0.02 and 0.06 of the N released from nitrification and denitrification respectively, forms $N_2O$. These fractions have been applied to histosol soils.

### 3.3.2.2. $N_2O$ in soil erosion

Soil residual N (Defra, 2010) estimates the existing mineral $NO_3^-$-N and $NH_4^+$-N, and the potential N available from mineralisation of organic matter within a given soil texture following a given crop. The PESERA soil erosion risk map (Kirkby *et al.*, 2004) predicts, at a 1 $km^2$ resolution, the quantity of soil (t $ha^{-1}yr^{-1}$) at risk of removal from erosion. The potential loss of residual $NO_3^-$ and indirect emission of $N_2O$ within eroded soil have been estimated using Equation 1:

*Equation 1*

$$N_2O_{(erosion)} = S_{eroded} * N_{soil\ 1,\ 2 \ldots n} * 0.0075 * 44/28$$

Where:

$S_{eroded}$ = mean weight of soil eroded (t $ha^{-1}$)
$N_{soil}$ = residual soil N per t of soil for soil texture 1, 2...n
0.0075 = Nitrogen leaching/runoff factor (kg $N_2O$-N $kg^{-1}$ N leaching / runoff)
44/28 = conversion $N_2O$-N to $N_2O$

### 3.3.2.3. $N_2O$ in surface run-off

Surface run-off has been calculated in response to the saturated hydraulic conductivity class (USDA, 2002), a measure of the potential for water to penetrate the soil profile, a product of soil type and likely compaction (land use) (Table 3.5). A low saturated hydraulic conductivity class indicates low potential for water to penetrate the topsoil and a higher risk of surface run-off. This is then used to derive the 'surface run-off class' (negligible, very low, low, moderate, high and very high) in combination with surface gradient for which the proportion of N of the total N applied present within run-off is devised as a factor. The field specific gradient (minimum, mean and maximum) has been calculated using ArcGIS® and is illustrated in Figure 3.

Table 3.5. Saturated Hydraulic Conductivity Class relative to soil texture and management.

| Soil type | Compacted | Land use | Saturated Hydraulic Conductivity Class |
|---|---|---|---|
| Sand | No | Cultivated land rough surface / UIG / TG yrs 1-2 | High |
| Sandy loam | No | Cultivated land rough surface / UIG / TG yrs 1-2 | High |
| Silty loam | No | Cultivated land rough surface / UIG / TG yrs 1-2 | Moderately High |
| Silty clay | No | Cultivated land rough surface / UIG / TG yrs 1-2 | Moderately Low |
| Clay | No | Cultivated land rough surface / UIG / TG yrs 1-2 | Moderately Low |
| Peaty | No | Cultivated land rough surface / UIG / TG yrs 1-2 | High |
| Sand | Topsoil | SIG / TG yrs 3-5 | High |
| Sandy loam | Topsoil | SIG / TG yrs 3-5 | Moderately High |
| Silty loam | Topsoil | SIG / TG yrs 3-5 | Moderately High |
| Silty clay | Topsoil | SIG / TG yrs 3-5 | Moderately Low |
| Clay | Topsoil | SIG / TG yrs 3-5 | Low |
| Peaty | Topsoil | SIG / TG yrs 3-5 | High |
| Sand | Subsoil | Cultivated land compacted | Moderately High |
| Sandy loam | Subsoil | Cultivated land compacted | Moderately High |
| Silty loam | Subsoil | Cultivated land compacted | Moderately Low |
| Silty clay | Subsoil | Cultivated land compacted | Low |
| Clay | Subsoil | Cultivated land compacted | Low |
| Peaty | Subsoil | Cultivated land compacted | High |

The implementation of a buffer strip of specified width within a field of known slope angle reduces the N in run-off by the estimated percentage given in Table 3.6 (from Dillaha *et al*., 1986). This is then converted to $N_2O$ using the IPCC (2006) methodology.

Table 3.6. Estimated impact of buffer strip width on surface run-off in response to slope gradient (from Dillaha *et al*., 1986).

| Buffer width | Slope | Gradient (°) | Average reduction |
|---|---|---|---|
| 2 m | Low | <10 | 82% |
| 4 m | Low | <10 | 83% |
| 6 m | Low | <10 | 85% |
| 10 m | Low | <10 | 88% |
| 2 m | Moderate | 10 to 20 | 74% |
| 4 m | Moderate | 10 to 20 | 76% |
| 6 m | Moderate | 10 to 20 | 77% |
| 10 m | Moderate | 10 to 20 | 81% |
| 2 m | High | ≥20 | 24% |
| 4 m | High | ≥20 | 26% |
| 6 m | High | ≥20 | 27% |
| 10 m | High | ≥20 | 31% |

Anaerobic soil conditions often proliferate where drainage is poor and water accumulates (Machefert *et al*., 2002), often in response to compacted high bulk density soils, in combination with high precipitation. Topsoil compaction, a risk on smaller particulate soils when wet (Houšková and Montanarella, 2007), may be problematic on permanent grassland where removal by cultivation is not possible. Compaction of the upper topsoil layers (to 20 cm depth) may be attributed to high stocking rates in addition to areas favoured by livestock such as adjacent to feeding troughs or under trees (Schils *et al*., 2008). Compaction in the lower soil layers (below 20 cm) is often a result of heavy farm machinery accessing fields when soils are wet (Houšková and Montanarella, 2007). Water is unable to penetrate compacted (low saturated hydraulic conductivity) soils (USDA, 2002) and, as a consequence, water run-off on compacted soils is greater. This is intensified further by steeper gradients within fields and when limited vegetation cover (for example preceding a spring sown crop) fails to intercept rainfall.

### 3.3.3. Methane ($CH_4$)

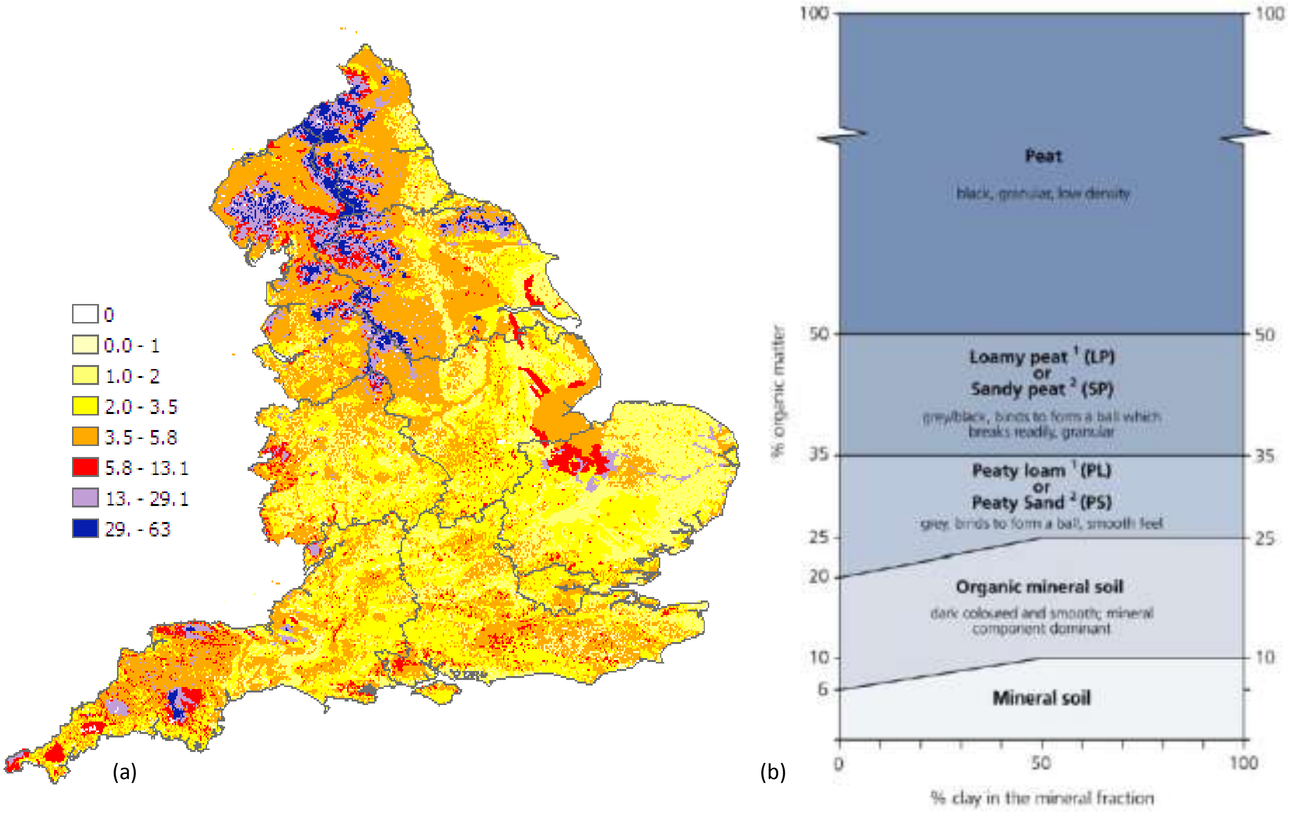
Enteric fermentation in ruminants, such as sheep and cattle, produces $CH_4$ (IPCC, 2006). The volume produced depends on the animal type, number and diet (Abberton *et al*., 2008; Freibauer *et al*., 2003; Moorby *et al*., 2007; Smith *et al*., 2008). Methane is also emitted during storage of both liquid and solid manures, although in greater quantities from the former (Freibauer *et al*., 2003) and in response to increased ambient storage temperature (for example during the summer as opposed to the winter). The method of manure storage and source (animal type) are further key drivers in determining the rate with which $CH_4$ is emitted (Monteny *et al*., 2006; Sommer *et al*., 2007).

Methane emissions from livestock systems, from the enteric fermentation of ruminant animals and from the handling of manures, have been calculated per livestock unit for BD2302 and BD5007 (Warner *et al*., 2008; 2011b) to account for dietary composition, and method of and mean temperature during manure storage (IPCC, 2006; Thomas, 2004; Williams *et al*., 2009). The same method has been adopted and $CH_4$ emitted from manures accounts for method of storage and volatile solid (VS) and starch content of the feed per kg dry matter (Feed into Milk (FiM) database) (Chadwick, 2005; IPCC, 2006; Thomas, 2004; Williams *et al*., 2009) adjusted for regional variation in mean temperature (IPCC, 2006; EDIT, 2012).

### 3.3.4. Carbon sequestration

Carbon is present in soils as soil organic carbon (SOC) but may be lost when subject to frequent, in particular annual, cultivation. Cultivated agricultural land typically has smaller quantities of carbon in soils and biomass than other land uses such as permanent grassland or woodland (Bradley *et al*., 2005; Dyson *et al*., 2009; Smith *et al*., 2008). A significant potential source of $CO_2$ emissions is from agricultural peat soils that form under wet anaerobic conditions (Schils *et al*., 2008). Maintenance of these conditions prevent the C contained within peat, which may be substantial, from oxidation and emission as $CO_2$. The loss of anaerobic conditions through land drainage creates aerobic soil conditions, conducive with peat decomposition $CO_2$ release (Schils *et al*., 2008). The emission of $CO_2$ from drained peat may be substantial. Carbon sequestration and its potential for enhancement within agricultural systems has been reviewed by a number of authors (for example Conant *et al*. (2001), Dawson and Smith (2007), Follett *et al*. (2001); Ogle *et al*. (2003); Ostle *et al*. (2009); Schils *et al*. (2008) and Soussana *et al*. (2004). Studies specific to the UK include Bradley *et al*. (2005), Dyson *et al*. (2009), Falloon *et al*. (2004), King *et al*. (2004) and Smith *et al*. (2000abc). The underpinning management techniques common to all these studies include reduced frequency of soil tillage and incorporation of organic matter (crop residues, farmyard manure, straw) on cultivated land, and on grassland, improvements such as fertiliser, lime application and mixed grass swards inclusive of N-fixing legumes. Carbon within soils may be removed and oxidised as a result of soil erosion, mitigated by several options listed in Table 1 of Technical Information Note 107 (Natural England, 2012).

The existing soil carbon baselines used in BD2302 and BD5007 (Warner *et al*., 2008; 2011) for different land management categories have been revised using the JRC soil organic carbon (Jones *et al*., 2005) and dominant soil texture data-sets (Panagos *et al*., 2012) in ArcGIS® at the 1 $km^2$ resolution. Where there is evidence that semi-natural habitats (for example moorland) have been converted to agricultural land (indicated by for example, implementation of moorland restoration options) the inventory accounts for the impact of restoration based on the potential soil C equilibrium of such habitats in pristine condition (Carey *et al*., 2008; Dyson *et al*., 2009). The percent SOC (Jones *et al*., 2005) spatial dataset has been reclassified to correspond with the soil types derived for a given soil organic matter (SOM) content by Natural England (2008) (Figure 3.4) for an assumed SOC to SOM ratio of 1:1.72 (IPCC, 2006).



From Natural England Technical Information Note TIN037

Figure 3.4. (a) Revised % soil organic carbon classification and (b) soil type and corresponding organic matter content in England.

Table 3.7. Revised % soil organic carbon classification and corresponding soil types, and estimated $CO_2$ (t $CO_2e$ $ha^{-1}$ $yr^{-1}$) emissions from degraded organic soils.

| Percent SOC | Soil type (<50% clay) | Soil type (>50% clay) | Emissions (degraded soils) |
|---|---|---|---|
| 0 – 1 | mineral | mineral | 0 |
| 1 – 2 | mineral | mineral | 0 |
| 2 - 3.5 | mineral | mineral | 0 |
| 3.5 - 5.8 | mineral | organo-mineral | 0 |
| 5.8 - 13.1 | organo-mineral | organo-mineral | [a]5.0 |
| 13.1 - 29.1 | peat (loamy / sandy) | peat (loamy / sandy) | 7.3 |
| 29.1 – 68 | peat | peat | 10.9 |

[a] *estimate*

#### *3.3.4.1. $CO_2$ from drained organic soils*

The drainage of high percent SOC (peaty) soils causes emission of $CO_2$, estimated at 10.9 and 7.3 t $CO_2$e $ha^{-1}$ $yr^{-1}$ $CO_2$ from drained lowland and upland peat in the UK respectively (Jackson *et al*., 2009). Cultivated peat soils are estimated to emit 15.0 t $CO_2$e $ha^{-1}$ $yr^{-1}$ (Freibauer, 2003). Estimated emissions relative to percent SOC are given in Table 3.7. The removal of drainage ditches ('grip' blocking) to restore the water table may remediate this although the impact may not occur immediately (Freeman *et al*., 2001).

#### *3.3.4.2. $CO_2$ from soil erosion*

When soil is eroded, the SOC contained within that previously undisturbed soil (Jones *et al*., 2005) has the potential to oxidise to $CO_2$. Estimates of CO2 emission attributed to soil erosion have been made with three JRC GIS datasets (Table 1):

1. Percent SOC (Jones *et al*., 2005)
2. Dominant soil texture (Panagos *et al*., 2012) and soil bulk density
3. Conversion of percent SOC to t SOC per t of soil to 30cm depth (Kirkby *et al*., 2004):

   *Arable: 1.46 - 0.0254 * ln(% clay) + 0.0279 * ln(% sand) - 0.026 * ln(% SOC)*
   *Temporary grass: 0.807 + 0.0989 * ln(% clay) + 0.106 * ln(% sand) - 0.215 * ln(% SOC)*
   *Permanent grass: 0.999 + 0.0451 * ln(% clay) + 0.0784* ln(% sand) - 0.244 * ln(% SOC)*
   *Other: 0.87 + 0.071 * ln(% clay) + 0.093* ln(% sand) - 0.254 * ln(% SOC)*

4. Soil erosion risk (t soil $ha^{-1}$) (Kirkby *et al*., 2004)

The dominant soil textural class provides values of percent clay and sand composition for use in the equations in (3) above. The PESERA soil erosion risk dataset categorises the potential weight of soil removed by erosion (t soil $ha^{-1}$ $yr^{-1}$) for which the quantity of C contained (calculated for a given percent SOC, soil bulk density and land use) may be derived with Equation 2 and summarised in Figure 3.5.

*Equation 2*

$$\text{SOC removed (tCO}_2\text{e ha}^{-1}\text{ yr}^{-1}) = \text{Soil erosion (t soil ha}^{-1}\text{ yr}^{-1}) \times \text{SOC (tCO}_2\text{e t}^{-1}\text{ soil)}$$

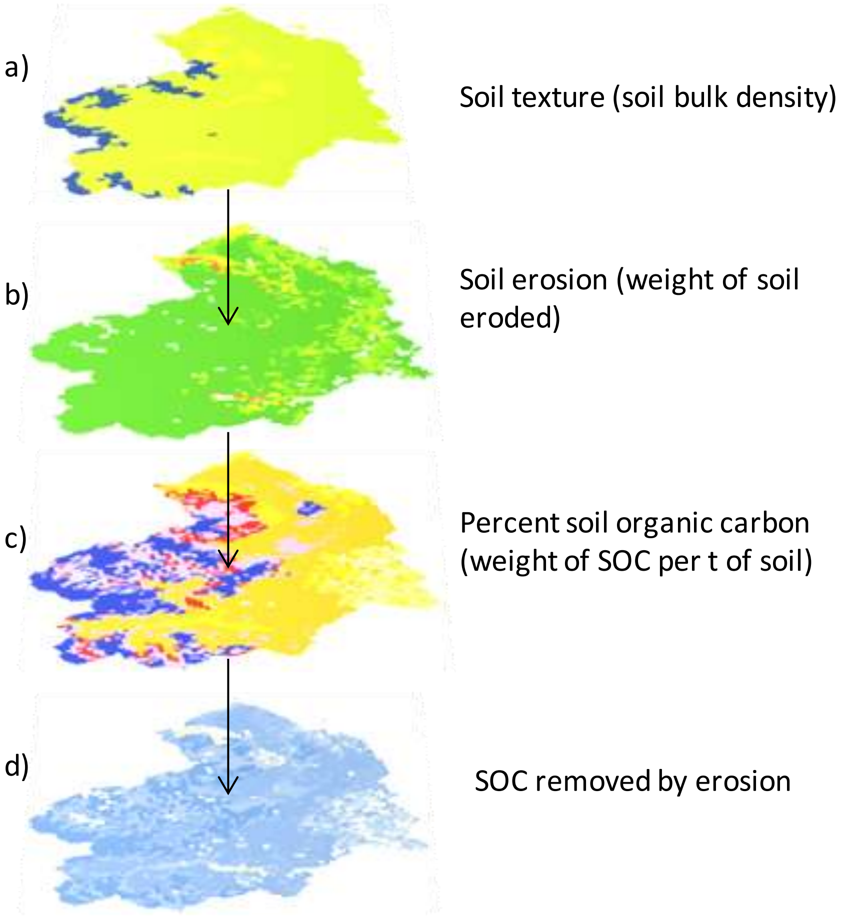


Figure 3.5. (a) Dominant soil texture (b) percent soil organic carbon (c) soil erosion risk (t soil ha$^{-1}$ yr$^{-1}$) and (d) potential SOC removed by soil erosion.

It is acknowledged that the resolution at 1 km$^2$ may be insufficient where smaller, localised risk areas exist within fields. The calculation of slope gradient (maximum and mean) within individual fields on each farm at the 10 m$^2$ resolution has been used to increase the spatial resolution and adjust the erosion risk category. For example, where an erosion risk of 1 is provided at the 1 km$^2$ resolution but steep gradients exist within individual fields for just 20 m$^2$, the risk category has been increased equivalent to the maximum PESERA risk value (Kirkby *et al*., 2004) within the local area for calculation of the impact of options targeted on specific areas of a field.

### *3.3.4.3. Carbon sequestered in soil*

The baseline SOC has been derived using the percent SOC (Jones *et al*., 2005) and dominant soil texture (Panagos *et al*., 2012) datasets (Figure 3.2). The processes governing the increase or decrease of C sequestered in soils of relevance to the options assessed in detail are summarised in Table 3.8.

Table 3.8. SOC accumulation (to 30 cm) from a change in land use on cultivated land. Stated range from literature and (average).

| Original land use | New land use | t $CO_2e$ $ha^{-1}$ $year^{-1}$ |
|---|---|---|
| Cultivated | Temporary grassland | 1.28 |
| | Fertilised permanent grassland | 1.10 – 6.97 (4.40) |
| | Sown unfertilised grassland | 1.10 – 6.97 (3.67) |
| | Sown unfertilised grass margins | 1.10 – 6.97 (3.67) |
| | Natural reversion | 0.55 – 2.20 (1.65) |
| | Hedgerow | 3.48 |
| | Scrub | 3.48 |
| | Broadleaved woodland / tree strips | 3.30 |
| | Conifer woodland | 3.30 |

A modification to the land use or management practice highlighted in Table 3.8 alters the potential SOC at equilibrium and induces a change, the annual rate of which is variable depending on the baseline and new land use or management practice (Dawson and Smith, 2007; Schils *et al*., 2008). Minimum tillage and undersown clover are predicted to increase SOC by 0 to 0.73 t $CO_2e$ $ha^{-1}$ $yr^{-1}$ and 0.55 to 1.47 t $CO_2e$ $ha^{-1}$ $yr^{-1}$ respectively (Dawson and Smith, 2007). The rate of change may be further impacted by the presence of topsoil or subsoil compaction (Louwagie *et al*., 2008). On cultivated land, measures to prevent soil erosion may reduce SOC loss (Ostle *et al*., 2009) but have negligible impact on crop yields. Temporary grassland tends to be high input and used to support high stocking rates or is used for winter feed production. The IPPC (2006) specifies management that improves the rate of grass growth (supplementary nutrient application and liming subject to crop recommendations, and clover in the sward) increases SOC accumulation (Conant *et al*., 2001; Follett *et al*., 2001; Ogle *et al*., 2003; Soussana *et al*., 2004) however periodic cultivation (e.g. every 5 years) will suppress this to a certain extent. The benefit of supplementary nutrient application is also specific to productive grassland where continued removal of foliage by high grazing levels of livestock requires enhanced grass growth rates to allow replacement. Its overall benefit is also dependent on the underlying soil type. Application of additional N to organic soils risks proportionally higher soil $N_2O$ emission from nitrification and denitrification (DeVries *et al*., 2003).

Table 3.9. SOC accumulation (to 30 cm) from a change in land use on grassland.

| Original land use | New land use | t $CO_2$e $ha^{-1}$ $year^{-1}$ |
|---|---|---|
| Temporary grassland | Permanent grassland | 0.73 |
| | Permanent grassland (shaded areas) | 0.37 |
| | Unfertilised grass margins | 0.73 |
| | Hedgerow | 0.55 |
| | Scrub | 0.55 |
| | Broadleaved woodland / tree strips | 0.37 |
| | Conifer woodland | 0.37 |
| | Marshy grassland | 2.93 |
| Fertilised permanent grassland | Hedgerow | 0.29 |
| | Increased grass species richness | 0.29 |
| | Broadleaved woodland / tree strips | 0.29 |
| Unfertilised grassland | Marshy grassland | 2.93 |

Extensively grazed grassland has the potential to increase grass species diversity which allows 'resource partitioning'. Nutrients are extracted from different layers within the soil at different times of the year. An enhanced 'ecosystem function' reduces direct competition between plant species allowing greater biomass growth and return of SOM and also SOC to the soil (Soussana *et al*., 2004). The reduction of livestock, or their removal during the winter when soils are wet, on grassland where there is high natural susceptibility to soil compaction in combination with high annual precipitation provides the opportunity to enhance grass rooting depth and biomass accumulation. Louwagie *et al*. (2008) predict that productivity may be decreased by up to 13% where topsoil compaction is present. This value has been used to provide an indication of the potential reduction in SOC equilibrium on high compaction risk soils (Table 3.10). Maize crops where subsoil compaction is not remediated assume a decrease in the SOC equilibrium and loss of SOC of between 0.04 and 0.13 t $CO_2$e $ha^{-1}$ $yr^{-1}$. The annual accumulation rate of SOC for a given change of land use or management practice has been adjusted in response to natural soil susceptibility to compaction (low, medium, high and very high) (Table 3.10) where management risks compaction (high stocking rates causing topsoil compaction, heavy machinery causing subsoil compaction). Non-compacted soils assume the value of low compaction.

Table 3.10. SOC accumulation (t $CO_2$e $ha^{-1}$) to 30 cm depth from a change in land use on temporary grassland in response to soil compaction.

| Original land use | New land use / practice | Low | Medium | High | Very high |
|---|---|---|---|---|---|
| Temporary grassland | Inclusion of legumes | 1.93 | 1.84 | 1.76 | 1.67 |
| | Permanent semi-improved grassland | 1.28 | 1.23 | 1.17 | 1.12 |
| | Permanent unimproved grassland | 0.73 | 0.70 | 0.67 | 0.64 |
| | Tree strip | 0.37 | 0.35 | 0.33 | 0.32 |

Soil organic carbon may be increased by a change in land use from a lower SOC land use (e.g. cultivated land) to one of a potentially higher SOC equilibrium (e.g. woodland, forestry or permanent grassland). The restoration of cultivated land or grassland to potentially high SOC containing habitats such as mire (bog) habitats or heather moorland may yield greater benefits. The restoration of habitats that contain deep peat soils, or that have potential to accumulate SOC in the long term are highlighted as priority measures for GHG mitigation (Schils *et al*., 2008; Smith *et al*., 2008; Regina *et al*., 2009). On individual farms such areas may be small in size and present where topography and altitude are conducive with their formation. The high percentage SOC in areas to the west of Northumberland (Figure 3.2), including the case study farm areas, are indicative of the presence of upland moorland or bog habitats, and the importance of their preservation for C storage highlighted. Risk of oxidation of these high soil C stores results from drainage and the creation of aerobic soil conditions (Freibauer, 2003; Jackson *et al*., 2009; Schils *et al*., 2008). Measures that remove drainage and restore these habitats potentially reverse the $CO_2$ release (Freeman *et al.,* 2001; Moorby *et al.,* 2007), the quantity of which is dependent on depth and percent SOC (Table 3.7). Deep histosol soils are indicative of deep peat soils, the percent SOC dataset (Jones *et al*., 2005) shows SOC to 30 cm depth.

A SOC baseline for each farm case study has been derived using the percent SOC and bulk density for individual soil texture classes described in section 3.3.4.2. For each case study farm, an SOC baseline has been assigned to individual fields where the key options under investigation are located. The SOC equilibrium potential maximum has been set as the highest SOC within the region for a given land use, dominant soil texture, altitude (above or below 300 m), annual rainfall and mean annual temperature. The potential to increase the SOC is calculated where the SOC is below this maximum. Where the maximum is already present it is assumed to be at equilibrium. The potential change in SOC and time to reach a new equilibrium is calculated with Equation 3 for the top 30 cm of the soil layer (IPCC, 2006).

*Equation 3*

$$T = (SOCeqb_{(new)} - SOCeqb_{(baseline)}) / R_{(SOC)}$$

Where:

$T$ = Time to establish new SOC equilibrium

$SOCeqb_{(new)}$ = potential SOC at equilibrium (t $CO_2$e ha$^{-1}$) of the new land use
$SOCeqb_{(baseline)}$ = SOC at equilibrium (t $CO_2$e ha$^{-1}$) of the baseline scenario (current land use)
$R_{(SOC)}$ = SOC accumulation rate (t $CO_2$e ha$^{-1}$ yr$^{-1}$) for a given change in land management

#### 3.3.4.4. Carbon sequestered in plant biomass

Biomass and the potential C (t $CO_2$e ha$^{-1}$) at equilibrium applicable to the priority options under consideration has been synchronised with the CORINE land cover GIS data-set (European Environment Agency, 2006) (Table 3.11).

Table 3.11. England CORINE land cover classes and corresponding biomass C at equilibrium.

| CORINE land cover classification | t $CO_2e$ ha$^{-1}$ |
|---|---|
| Non-irrigated arable land | 8.1 |
| Pastures (semi-improved and temporary grassland) | 5.9 |
| Natural (unimproved) grasslands | 8.8 |
| Moors and heathland (including mires) | 6.2 |
| Woodland - broad-leaved | 392.8 -513.3 |

The land cover with the lowest biomass is heavily grazed grassland, in contrast to mature woodland (Table 3.11) (Milne and Brown, 1997; Dawson and Smith, 2007) although a longer growth period is required for woodland to attain equilibrium. Annual biomass C accumulation has assumed a linear annual rate of accumulation although the actual rate is subject to the age of the tree (stage of growth) and the species (Milne and Brown, 1997). Cultivated land achieves full biomass potential within one year (Falloon *et al*., 2004).

## 3.4. Impact assessment

The inventory described in section 3.3 has been applied to the management scenarios of ES options and a GHG balance calculated using eq t $CO_2$ ha$^{-1}$ yr$^{-1}$ to standardise the GHG emissions from each option management scenario, minus the C sequestered relative to the baseline conditions defined for each farm case study to give the total equivalent net GHG emissions (t $CO_2$ ha$^{-1}$ yr$^{-1}$), the net direction (positive or negative) of C flux to the atmosphere, for each evaluated ES option:

*Equation 4*

$$GHG\ balance = (D + I_a + I_m + S_{N2O} + S_{CH4} + S_{CO2} + L_{N2O} + L_{CH4}) - (Cseq_{(SOC)} + Cseq_{(biomass)})$$

Where:

$D$ = direct emissions from machinery operation
$I_a$ = indirect emissions agro-chemical manufacture
$I_m$ = indirect emissions machinery manufacture / depreciation
$S_{N2O}$ = soil $N_2O$ emission
$S_{CH4}$ = soil $CH_4$ emission
$S_{CO2}$ = soil $CO_2$ emission
$L_{N2O}$ = $N_2O$ emissions from livestock
$L_{CH4}$ = $CH_4$ emissions from livestock
$Cseq_{(SOC)}$ = C sequestered in soil during year n
$Cseq_{(biomass)}$ = C sequestered in plant biomass during year n

The GHG balance of options may vary between the first year and subsequent years due to differences in the management required initially (for example the mowing of grass strips more frequently during year 1 to prevent pernicious weeds). The total $CO_2e$ emissions (t $CO_2e$ ha$^{-1}$year$^{-1}$) and the net direction (positive or negative) to the atmosphere for each ES option evaluated will be calculated relative to the baseline conditions on a per year basis for a mean of 5 years to account for variability in option management during the initial phases of implementation.

*Equation 5*

$$\triangle \text{GHG flux} = \text{GHG balance option}_{(n)} - \text{GHG balance baseline}$$

Where: $\triangle$GHG flux = change in net GHG balance during year n (years 1 to 5)

GHG balance option$_{(n)}$ = net GHG balance of the option during year n (years 1 to 5)

GHG balance baseline = net GHG balance of the baseline scenario

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 biomass C for the specified year as a result of the management change, minus the GHG emissions from the original baseline scenario. This also accounts for any initial loss of C from a change in management (for example, scrub removal).

## 3.5. Impact on greenhouse gas emissions inclusive of on-farm displacement

### 3.5.1. Yields

The impact on yields has been calculated at two spatial scales:

**Individual field scale:** to allow the impact of specific options to be quantified more accurately. For example, where option 1 is implemented on Area A the direct impact or change ($\triangle$) in the yield of Area A can be calculated using Equation 6:

*Equation 6*

$$\triangle \text{ Pr Area A} = P_r \text{ Area } A_x - P_r \text{ Area } A_y$$

Where: $P_r$ is yield (tonnes or litres of output of commodity X per ha)

$A_x$ is yield Area A before implementation of Option 1

$A_y$ is yield Area A after implementation of Option 1

**Whole-farm scale:** The implementation of Option 1 may also result in alteration to yields of areas elsewhere on the farm (where for example yield is increased in Area B in response to a reduction in yield in Area A). The total change in whole farm yield due to the implementation of Option 1 ($\triangle$ $P_r$ Option 1) is given in Equation 7:

*Equation 7*

$$\triangle P_r \text{ Option } 1 = \triangle P_r \text{ Area A} + \triangle P_r \text{ Area B}$$

Where: $\triangle P_r$ Area A is change in productivity Area A

$\triangle P_r$ Area B is change in productivity Area B

### 3.5.2. Scale of displacement

From the Tender: '*Displacement is caused when emission savings achieved through participation in ES (eg reduction in emissions due to ceasing nitrogen fertiliser inputs), leads to a loss of farm production, which is in turn compensated for by an increase in production outside of the ES area (either on-farm or off-farm), producing increased GHG emissions*'.

The impact of each priority option on yields (option area and applicable areas outside the option) calculated per case study farm has been used to estimate the scale of displacement (where there is an increase in production outside the option area on-farm). Any change in production in Area B (section 3.5.1) represents on-farm displaced production. The $\triangle P_r$ Area A may be used to categorise the risk of displaced production of each priority option, while $\triangle P_r$ Option 1 (the net impact on on-farm productivity overall) may be used as an estimate of the risk of off-farm displacement. The on-farm displaced production has been converted to a per ha of option equivalent for each farm case study. Where a range in displacement has been identified between farms, a 'best and worse' case scenario has been undertaken, with caveats stated, for the scaling up of the overall impact to the national level and the ES scheme as a whole, using option uptake statistics provided by Natural England.

### 3.5.3. Impact assessment with on-farm displacement and net greenhouse gas mitigation

Where option 1 is implemented on Area A the change ($\triangle$) in net GHG emissions of Area A (t $CO_2e$ $ha^{-1}$) can be calculated (Equation 8) as:

*Equation 8*

$$\triangle \text{GHG flux Area A} = \text{GHGbalance Area } A_x - \text{GHGbalance Area } A_y$$

Where: GHG flux is change in GHG emissions of Area A

$A_x$ is GHGbalance Area A before implementation of Option 1

$A_y$ is GHGbalance Area A after implementation of Option 1

The implementation of Option 1 may also result in alteration to the GHG balance of areas elsewhere on the farm (where for example yield is increased in response to the reduction in productivity in Area A by an increase in inputs to Area B). The total change in the farm GHG balance (t $CO_2e$ $ha^{-1}$), including displacement ($\triangle$ GHG $flux_{(DISP)}$), due to the implementation of Option 1 is (Equation 9):

*Equation 9*

$$\triangle \text{ GHG flux}_{(DISP)} \text{ Option 1} = \triangle \text{ GHG flux Area A} + \triangle \text{ GHG flux Area B}$$

Where: $\triangle$ GHG flux Area A is change in GHG emissions of Area A

$\triangle$ GHG flux Area B is change in GHG emissions of Area B

A negative $\triangle$ GHG flux indicates a decrease in net GHG emissions (including displacement) relative to the baseline, while a positive $\triangle$ GHG flux an increase. A net decrease in $\triangle$ GHG flux$_{(DISP)}$ results where the decrease in $\triangle$ GHG flux Area A is greater than any increase in $\triangle$ GHG flux Area B. The areas impacted (A and B) may cover different areas in total. For example, a buffer strip (Area A) 6 m wide and 500 m long covers 0.3 ha. The remainder of the field (Area B) over which an influence is exerted may cover 5 ha. The $\triangle$ GHG flux$_{(DISP)}$ Option 1 has been converted to a per ha equivalent based on the relative size ratios of the respective areas to each other and the combined $\triangle$ GHG flux.

The $\triangle$ GHG flux$_{(DISP)}$ quantifies displacement on a per unit area basis. An increase in emissions from $\triangle$ GHG flux Area B may be coupled with an increase in yield of commodity X which may be proportionally greater or lower to the additional inputs applied. Calculations have been made to assess the impact of the priority options, and the change in management where applicable, within associated areas of displacement on GHG emissions per unit of yield. Any increase or decrease in yield combined with an increase or decrease in GHG emissions, where applicable, is displayed relative to the baseline GHG emissions per unit of commodity. A decrease in GHG emissions per unit of commodity associated with Option 1 relative to the baseline is shown as a negative value. The greater the magnitude of the negative value, the greater the decrease in emissions and vice versa for an increase (positive value) in emissions (Equation 10):

*Equation 10*

$$\triangle\text{GHG flux}_{(DISS\ PROD)} \text{ Option 1} = (P_r \text{ Option 1} / \text{GHG flux}_{(DISP)} \text{ Option 1}) - (P_r \text{ Baseline} / \text{GHG flux Baseline})$$

Where: GHG flux$_{(DISS\ PROD)}$ Option 1 is GHG flux (including on farm displacement) of Option 1 per unit of commodity (t $CO_2$e per t or livestock unit)

$P_r$ Option 1 is the commodity yield for Option 1 (t or livestock units)

GHG flux Option 1 is the mean farm GHG balance, including displacement, due to the implementation of Option 1 (ha)

*Note: Equation 10 is calculated with the following caveats. Stated yields are, in addition to variation between farms, also subject to variation on the same farm between years in response to climatic variables and individual field characteristics. A range of typical yields were provided by the land manager and these have been stated* *and accounted for in the overall aggregation of results and calculation of $\triangle P_r$ Option for individual options.*

# 4.0 Results

## 4.1 Case study baseline variables

The farm specific variables for the 15 case study farms have been summarised previously in Table 3.3. The following section summarises the results of implementation of priority options on the chosen case study farms, and the impact on where applicable on yields within areas A and B described in section 3.5.

## 4.2 Priority options

The priority options are classed within one of three groups:

1. Options assumed to have no displacement (validation of the assumption that there is no impact on yield)
2. Options that remove part of a field from production and the extent of displacement (validation of assumption that there is no impact on management outside the option boundary either within the same field or other fields on-farm)
3. Habitat creation options and the scale of displacement (validation of assumption that there is no impact on management outside the option boundary on other fields on-farm)

Aggregated summary results are given in Tables 4.1. – 4.5.

### 4.2.1 Options assumed to have no displacement

#### *4.2.1.1 Management of maize crops to reduce soil erosion (EJ2)*

The harvest of maize may occur until late October / early November to maximise ear ripening (AgroBusiness Consultants, 2012). Maize harvested in close proximity to these dates are more likely to be followed by a spring sown crop. This risks an uncropped area being present during winter and if this remains unvegetated and compacted (a risk after maize crops due to the type of machinery used) it is vulnerable to erosion and surface run-off (Natural England 2010a). Three choices are available for the management of maize to reduce erosion (Natural England, 2010a) based on which the scenarios for EJ2 have been created. The baseline maize scenario assumes non-vegetated compacted soil post harvest susceptible to erosion and surface run-off, the magnitude is defined for farm specific baselines initially in response to the PESERA soil erosion risk map, tailored to the field level by use of field gradient and soil management category (Table 3.5). Entry into the option reduces the risk as follows:

1. *Harvest by 1 October and plough or cultivate to leave a rough surface, ideally within 2 weeks of harvest, to reduce subsequent soil erosion*. A spring cereal preceded by previously bare compacted soil post maize harvest is replaced by a spring cereal preceded by soil with a rough surface. During year 1 (maize crop) there is no

change, year 2 (spring cereal) a reduction in erosion and run-off. Baseline soil compaction decreases root penetration and SOC accumulation.

2. *Harvest by 1 October and establish an autumn-sown crop*. A spring cereal preceded by previously bare compacted soil post maize harvest is replaced by a winter cereal and soil with a rough surface. During year 1 (maize crop) there is no change, year 2 (winter cereal) a reduction in erosion and run-off (Table 3.5). There is an increased yield in year 2 (increase in Pr Area B).
3. *Undersow the maize with a grass- or clover-based mixture and after harvest (ideally within 2 weeks), remove any areas of soil compaction*. Year 1 maize undersown with grass / clover mixture, year 2 undersown grass / clover crop plus (a) spring cereal (as for choice 1 above). The aspect of the field slope is assumed to exert an influence. On a northern aspect there is increased shading and clover establishment, no impact on N fertiliser substitution and a 50% reduction of run-off and erosion and SOC increase, compared to full cover crop establishment (other aspects). In year 2 there is no impact on the N fertiliser application rate to the following crop since it is assumed to be removed during the February preceding a spring crop. Nitrogen is not fixed during the winter.
4. *Maintenance* (no change in management, farm manager undertaking one of options 1 – 3 already)

No impact on maize yield (△Pr Area A) was stated for any case study farm where EJ2 was present. A preference was given to the sowing of a winter cereal crop post harvest by the case study farms assessed. In some cases, this did not result in a change of management to that previously undertaken on the farm. For the sake of completeness, calculations have been made for all three available management scenarios and baselines. Choice 3 (undersown maize) was not encountered during farm visits and is a hypothetical calculation. Scenarios relate to two main farm types, dairy (feed consumed mainly on farm by dairy cattle) and non-dairy mixed (a proportion sold off farm). The latter applied negligible FYM due to stock being grazed outside for the majority of the year. It was also noted that in one case, agreements were recently implemented for which no notable alteration to yield had been noted at that time. Case study 5 noted the drilling of the following winter cereal crop in the latter part of September as opposed to the beginning (but well within the required timescale to satisfy EJ2 management requirements) had resulted in some water erosion of soil due to reduced ground crop cover preceding the winter compared to previous years, coupled with above average winter rainfall in the autumn and winter of 2012.

Choice 3 (a hypothetical calculation) has the greatest potential to reduce emissions although potentially subject to local field specific variables such as the aspect and gradient of the slope in combination. The stated Pr maize (fresh weight as forage) ranged from 40.0 – 55.0 t $ha^{-1}$. Area A (Table 3.5) is the field that contains maize (year 1). Area B assumes the same field as Area A post maize harvest when EJ2 has moved the maize crop elsewhere on the farm as part of a rotational option. The predicted mitigation potential was greatest where high erosion risk land and steeper field gradients were present in combination with high percent SOC. The smallest impact on GHG emissions via this pathway was calculated for Case study 6 and correlated with fields of low (<5$^{o}$) gradient.

Table 4.1. Aggregated change in GHG flux (t $CO_2$e ha$^{-1}$ yr$^{-1}$) including on-farm displacement for option EJ2 (Management of maize crops to reduce soil erosion) assumed to have no displacement.

| **Scenario** | ***Equation 6*** | | ***Equation 8*** | | ***Equation 9*** | ***Equation 10*** |
|---|---|---|---|---|---|---|
| | ^Pr Option Area A | ^Pr Option Area B | ^ GHG flux Area A | ^ GHG flux Area B | ^GHG flux$_{DISP}$ | GHG flux$_{DISS\ PROD}$ |
| EJ2 - Management of maize crops to reduce soil erosion (scenario 1) - year 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| EJ2 (scenario 1) - year 2 spring cereal (+ erosion mitigation) | 0 | 0 | 0 | -0.033 to -0.171 | -0.033 to -0.171 | -0.006 to -0.026 |
| **Change after 2 years** | **0** | **0** | **0** | **-0.033 to -0.171** | **-0.033 to -0.171** | **-0.006 to -0.026** |
| EJ2 - Management of maize crops to reduce soil erosion (scenario 2) - year 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| EJ2 (scenario 2) - year 2 winter cereal replaces spring cereal + erosion | 0 | 2.5 to 3.0 | 0 | 1.250 to 1.806 | 1.250 to 1.806 | -0.025 to -0.044 |
| **Change after 2 years** | **0** | **2.5 to 3.0** | **0** | **1.250 to 1.806** | **1.250 to 1.806** | **-0.025 to -0.044** |
| EJ2 - Management of maize crops to reduce soil erosion (scenario 3) undersown maize + poor clover establishment | 0 | 0 | -1.194 to -0.504 | 0 | -1.194 to -0.504 | -0.010 to -0.030 |
| EJ2 (scenario 3) - year 2 spring cereal + poor clover establishment | 0 | 0 | 0 | -0.171 to -0.040 | -0.171 to -0.040 | -0.007 to -0.026 |
| **Change after 2 years** | **0** | **0** | **-1.194 to -0.504** | **-0.171 to -0.040** | **-1.234 to -0.675** | **-0.037 to -0.036** |
| EJ2 - Management of maize crops to reduce soil erosion (scenario 3) undersown maize | 0 | 0 | -2.474 to -2.446 | 0 | -2.474 to -2.446 | -0.062 to -0.047 |
| EJ2 (scenario 3) - year 2 spring cereal | 0 | 0 | 0 | -0.178 to -0.048 | -0.178 to -0.048 | -0.027 to -0.009 |
| **Change after 2 years** | **0** | **0** | **-2.474 to -2.446** | **-0.178 to -0.048** | **-2.625 to -2.522** | **-0.074 to -0.071** |

#### *4.2.1.2a Under sown spring cereals on organic land (OG1)*

The organic arable crop rotations followed a similar format between farms, the sequence of and type of crops varied slightly but the crop of relevance to option OG1 within the rotation was the spring cereal immediately preceding a grass clover ley (of variable duration between 2 and 5 years). For the following generalised rotation: spring wheat - winter oats - one year red clover - winter wheat - spring barley – 2 to 5 year grass and clover ley the spring barley crop has been modified to represent entry into OELS. The scenarios are summarised as follows:

1. Spring barley not undersown (receives N from clover before the previous winter wheat crop) with a 2 – 5 year grass / clover fertility building crop sown after the harvest of the spring barley crop
2. Spring barley is undersown to establish the 2 - 5 year grass / clover ley, no cultivation is required after harvest of the spring barley crop to drill the grass / clover mixture. Where there is poor establishment the grass / clover mixture is resown

Where a crop is undersown the crop seed and undersown legume mix (typically clover and grass) are sown in close proximity temporally and grow simultaneously to one-another. The clover mixture (30% with grass) supplies, subject to the degree of establishment, N to the undersown crop. On cultivated arable land estimates vary, but between 30 and 100 kg N $ha^{-1}$ $yr^{-1}$ may be provided to the undersown crop depending upon establishment and the time of year when N is required by the crop (a proportion of the overall N may be required before N fixation begins) (Defra, 2010). There is no assumed impact on leaching and $N_2O$ emission during winter, in contrast to a winter cover crop drilled during early autumn and removed the following spring that has potential to reduce N losses.

For the case study farms assessed, the undersown spring cereal on organic land did not alter the rotation but typically modified the management of a spring cereal crop immediately before and after in response to entry into the agreement. Modification to the rotation occurred in Case study 15 (the removal of kale and turnip) although this was in response to persistent cabbage stem flea beetle *Psylliodes chysocephala* infestation and limited opportunity for its control, rather than due to entry into ES.

Aspect (north facing) and shading was stated as an influencing factor on the establishment of the undersown grass / clover ley in Case study 3. The influence of aspect and gradient was not stated as having a notable effect by other case study farm managers, in part because local site topography did not provide the appropriate combination of aspect and gradient where the option was located. A scenario has been created to assess the potential impact of poor establishment of the undersown grass / clover crop although it is acknowledged that this may be attributable to a number of factors. Where establishment is poor in option EG1, supplementary N may be applied to maintain optimal N supply. In OG1 / OHG1 the ley requires re-establishment (cultivation and drilling of seed).

The potential to sow then establish the grass/clover ley eliminates one seed bed preparation set of operations from the rotation (assigned between the four crops in the rotation). This has greater potential to reduce GHG emissions on fine soils (Table 3.4) but where there is a history of poor establishment there is no change as the ley has to be resown. The impact of the undersown crop, and of poor clover establishment where applicable, is realised during the spring and summer. On organic land, where supplementary N is not applied, there is a potential impact on yield rather than inputs of N. For the case study where poor establishment had occurred, resolution of difference in crop yield within field areas was not sufficient to establish with confidence the overall impact on crop yield, yields were an aggregated estimate of the whole field. The calculations (Table 4.2) have not adjusted yield in response to poor undersown grass / clover establishment but potential benefits that are not realised include additional N and suppression of weeds. A decrease in yield would be anticipated. Aspect is assumed to make no difference between baseline and option during autumn and winter (to erosion and run-off) but impacts further growth during the spring when N-fixation is required. Where the establishment of the grass / clover ley is satisfactory, erosion post harvest of a spring cereal is reduced from that of a recently cultivated and sown seedbed to that of temporary grassland post year 1. Clover fixes N at rates equivalent to between 40 and 100 kg N $ha^{-1}$ on cultivated land. Where it is able to establish in grassland over a period of years a 30% mixture may fix in the region 180 kg N ha-1. This N, if not utilised by the crop, will be subject to leaching in the same manner as supplementary N fertiliser application. Abberton (2008) estimate that $N_2O$ emission from clover within grassland may be comparable to grassland fertilised with 200 kg N $ha^{-1}$. Surface run-off is calculated as negligible due to the N being fixed below ground, the N is at risk of loss as residual N during erosion. A further stated benefit of undersown spring cereals on organic land was a reduction in weed populations (Case study 15) and the need for an equivalent additional shallow cultivation per crop.

#### *4.2.1.2b Under sown spring cereals (EG1)*

Option EG1 was not represented in the case study farms however Case study 1 identified general baseline management on non-organic land prior to conversion and entry into OELS. This has been used to devise scenarios for EG1. Under option EG1 a spring cereal substituted a winter cereal. Spring cereal crops have a yield decrease relative to autumn sown cereals typically of around 30% (Nix, 2012), which was accounted for in previous GHG calculations of Environmental Stewardship options (Warner *et al*., 2011b). A variable not previously included within the assessment of yield was the impact of below average rainfall during the spring. The poor establishment of spring sown cereals compared to winter cereals was commented on by a number of farm managers in the south-east of England. Yield reductions of up to 40% were stated for spring sown cereals where the crops had eventually been harvested although complete crop failure had also occurred. Option EG1 was not present on case study farms in Northumberland, however it was stated by farm managers within this region that no noticeable yield reductions were evident for spring crops in recent seasons. The severity of lower than average rainfall was not of the magnitude of that experienced in the south-east of England. Yield reduction risk has been estimated based on annual rainfall and the available soil water content of the underlying dominant soil texture. Lower annual rainfall, higher evapo-transpiration and lower available soil water content have been used as a surrogate measure to indicate areas at greatest risk to poor spring crop growth. There is a greater potential yield loss attributed to option EG1 where a spring cereal replaces a winter cereal in these areas. The following scenarios have been constructed:

1. Spring cereal to undersown spring cereal
2. Winter cereal to undersown spring cereal

The impact of the undersown crop, and of crop shading on northern aspects where applicable, is realised during the spring and summer, specifically inputs of N. Erosion or leaching during the autumn and winter before the spring sown crop does not change.

#### *4.2.1.2c Under sown spring cereals on HLS organic land (OHG1)*

The management of organic HLS land is tailored to specific fields on a particular farm. Undersown spring cereals substituted existing spring cereal crops as described previously for OG1 but with farm specific management modifications. They included a stated reduction in seed rate (Case study 1 as part of OS2) and the prohibition of lime application (Case study 15). No areas of poorer grass / clover establishment were identified by farm managers for either case study farm although a gradual decline in soil pH could potentially correlate with a decrease in grass and cereal silage yields in the future. This would require evaluation at the end of the agreement period.

Table 4.2. Change in GHG flux (t CO$_2$e ha$^{-1}$ yr$^{-1}$) including on-farm displacement for option EG1 and OG1 / OHG1 (Undersown spring cereal). *Note: the poor clover establishment scenario utilises data from one case study farm*.

| Scenario | Equation 6 | | Equation 8 | | Equation 9 | Equation 10 |
|---|---|---|---|---|---|---|
| | ^Pr Option Area A | ^Pr Option Area B | ^ GHG flux Area A | ^ GHG flux Area B | ^GHG flux$_{DISP}$ | GHG flux$_{DISS\ PROD}$ |
| OG1 / OHG1 - Undersown organic spring cereal + poor clover establishment (scenario 2) baseline organic spring cereal | 0 | 0 | 0 | 0 | 0 | 0 |
| OG1 / OHG1 - Undersown organic spring cereal other aspect (scenario 2) baseline organic spring cereal | 0 | 0 | -0.04 to -0.07 | 0 | -0.04 to -0.07 | -0.01 to -0.02 |
| | | | | | | |
| EG1 - Undersown spring cereal + poor clover establishment (scenario 1) baseline spring cereal | 0 | 0 | -0.49 | 0 | -0.49 | -0.09 to -0.08 |
| EG1 - Undersown spring cereal (scenario 1) baseline spring cereal | 0 | 0 | -1.88 to -2.03 | 0 | -1.88 to -2.03 | -0.32 to -0.33 |
| | | | | | | |
| EG1 - Undersown spring cereal + poor clover establishment (scenario 1) baseline winter cereal | -2.7 to -3.0 | 0 | -1.58 to -1.61 | 0 | -1.58 to -1.61 | 0.06 to 0.007 |
| EG1 - Undersown spring cereal (scenario 1) baseline winter cereal | -2.7 to -3.0 | 0 | -2.93 to -3.17 | 0 | -2.93 to -3.17 | -0.17 to -0.19 |
| | | | | | | |
| EG1 - Undersown spring cereal + poor clover establishment (scenario 1) baseline winter cereal + below average spring rainfall | -4.5 to -5.1 | 0 | -1.58 to -1.61 | 0 | -1.58 to -1.61 | 0.55 to 0.57 |
| EG1 - Undersown spring cereal (scenario 1) baseline winter cereal + below average spring rainfall | -4.5 to -5.1 | 0 | -2.93 to -3.17 | 0 | -2.93 to -3.17 | 0.12 to 0.17 |
| | | | | | | |
| HD3 - Low depth, non-inversion cultivation on archaeological features (scenario 1) baseline winter cereal | 0 | 0 | -0.46 | 0 | -0.46 | -0.06 |

#### *4.2.1.3 Low depth, non-inversion cultivation on archaeological features (HD3)*

Entry into HD3 did not impact crop yield or significantly alter the baseline crop rotation except that potatoes, previously grown 1 year in 5, were removed from the rotation (Case study 14). No loss of yield for crops that remained within the rotation post agreement (cereals and winter oilseed rape) had been noted by farm managers. In the south-east it was acknowledged that differences in weather patterns between years (prolonged dry springs and wet summers) would have masked any potential impact on crop yields since entering into the agreement.

Minimum tillage cultivates the top 5 cm only of the soil profile. The presence of a minimum tilled seedbed has the potential to reduce erosion and surface run-off (the cultivated top 5 cm permits water infiltration), particularly during the autumn and winter preceding a spring sown crop. Two scenarios have been created:

1. Winter cereal
2. Spring cereal

The location of Case study farms 7 and 14 on lighter soil textures meant blackgrass was not stated as being problematic, consequently additional herbicide applications were not required compared to the baseline crop management regime.

### 4.2.2 Options that remove part of a field from production and the extent of displacement

#### *4.2.2.1 Grass buffer strips on cultivated land (EE1, EE2 and EE3)/ 6m buffer strips on cultivated land next to a watercourse (EE9)*

No evidence of additional land being designated for cultivation or inputs being increased in other parts of the field in response to the implementation of buffer strips on cultivated land was evident in response to interviews with farm managers. It is acknowledged that some agreements were relatively new (18-24 months since inception) but no stated changes in management or crop yield outside the option ES boundaries had been observed to date. Farm managers stated that economic optimum was already achieved and while additional ‘greening’ of the crop may result from increased supplementary nutrient application rates, this did not justify the additional cost as the increase in yield would be negligible.

Grass buffer strips convert cultivated land to permanent unimproved grass. Two scenarios have been created:

1. Winter cereal
2. Spring cereal

An important property of grass buffer strips is their capacity to intercept and reduce surface run-off, and reduce soil erosion.  As such, their presence where erosion is a risk renders their GHG emissions reduction beyond that of purely the removal of cultivation and associated agro-chemical inputs.  Although zero N is applied to the strip, it is credited with the dissipation of run-off from neighbouring cultivated land, the proportion of which is dependent on the width and gradient of the slope (Table 4.3). This is highly field specific, and further specific to location within the field.  For example, a buffer strip at the top of a slope will exert a negligible influence on interception of run-off from the remainder of the field.  Strips located on the field edge perpendicular to the slope prevent run-off equivalent to the buffer strip width (2 – 10 m) while those at the base of the slope have potential to intercept run-off from the remainder of the slope.  In reality, field boundaries are not located at perfect right-angles to gradients and so will intercept run-off to varying degrees depending on field shape, gradient, width and location.  The grass buffer strips in Case study 6 were present on flat cultivated land for which the additional mitigation potential from run-off interception was negligible.

The impact on baseline crop yield (Pr Area A) by removal of cultivation and replacement with buffer strips did, however, vary depending on the location of the option agreement and the local field characteristics.  These options are applicable to the field boundaries (edges) of cultivated land and, as a consequence, may be located immediately adjacent to woodland, hedgerow, grass strips or water courses.  Strips located immediately to the north / north-east of mature woodland did not, according to one farm manager, replace yielding crops in the outer 3 – 4 m.  The crop was sown and received inputs as per recommendations and subject to observation of appropriate buffer widths for crop protection products but the grain within the outer 3 - 4 m tended not to ripen sufficiently to be harvested.  Grain yield in these areas tended to be negligible although the insufficiently ripened crop had potential for use as silage.  If these areas have received inputs in addition to cultivation but either without or with limited yield, then mitigation (a reduction in GHGs without compromise of yield) has resulted.

Declines in crop yield due to restricted crop protection product application were estimated by farm managers to be up to 10 % depending on the number and nature of products.  This would be applicable to crop yield immediately adjacent to hedgerows or woodland (beyond the Cross Compliance buffer strips) within a given buffer width. Where watercourses are present (option EE9), the estimated decrease in yield of 10% may occur but the distance into the crop depends on the products applied, method and the nature (dimensions and presence of water) of the watercourse.  Where a Local Environment Risk Assessment for Pesticides (LERAPS) is permitted (the product is Category B) this distance may be between 1 and 5 m.  An ES grass buffer strip of 6 m may experience full yield loss only in the inner 1 - 5 m depending on the products, dose and method of application.  The estimated yield reduction for buffer strips (Table 4.3) has been determined based on the proportion of the strip likely to experience a decrease in yield (different proportions depending on width), the magnitude of that decrease and whether adjacent to a watercourse (EE9) and potentially subject to a LERAPS assessment.  The non-spraying of the outer part of the crop does not reduce the number of machinery operations because the machine will pass through the area as normal, but turn off the spray boom for the required width.

One criticism of grass buffer strips by farm managers was the potential for increase in grass weed species such as sterile brome *Bromus sterilis* and *Fescue*s in the cropped area immediately adjacent to the buffer strips.  This had, in some locations, required modification to the herbicide treatment, typically a change in the active ingredients applied rather than an additional herbicide application.  The small quantity of active ingredient applied within pesticides as a rule has a minor impact on agricultural GHG emissions although an increase would be more notable if a further application was required (an additional field operation with a sprayer).

Table 4.3. Change in GHG flux (t $CO_2e$ $ha^{-1}$ $yr^{-1}$) including on-farm displacement for options EE3 and EE9 (6m grass buffer strips on cultivated land), EF1 (Field corner management), EE10 (6m grass buffer strips on intensive grassland), HE10 (Floristically enhanced grass margin), HF7 (Beetle banks) and HJ5 (In-field grass areas to prevent erosion or run-off). Where yields are removed completely the GHG $flux_{DISS\ PROD}$ is expressed as t $CO_2e$ $ha^{-1}$.

| Scenario | ***Equation 6*** | | ***Equation 8*** | | ***Equation 9*** | ***Equation 10*** |
|---|---|---|---|---|---|---|
| | ^Pr Option Area A | ^Pr Option Area B | ^ GHG flux Area A | ^ GHG flux Area B | ^GHG $flux_{DISP}$ | GHG $flux_{DISS\ PROD}$ |
| EE3 - 6m buffer strips on cultivated land (baseline winter cereal) | 0 to -9.25 | 0 | -9.85 to -9.59 | 0 | -9.85 to -9.59 | -9.85 to -9.59 |
| | | | | | | |
| EF1 - Field corner management (baseline winter cereal) | -7.5 to -9.25 | 0 | -9.83 to -9.56 | 0 | -9.83 to -9.56 | -9.83 to -9.56 |
| | | | | | | |
| EE10 - 6m buffer strips on intensive grassland next to a watercourse (haylage) | [a]-9.0 to -10.0 | 0 | -4.75 | 0 | -4.75 | -4.75 |
| | | | | | | |
| HE10 - Floristically enhanced grass margin (scenario 1) (baseline winter cereal) | -7.5 to -9.25 | 0 | -9.85 | 0 | -9.85 | -9.85 |
| | | | | | | |
| HF7 - Beetle banks (baseline winter cereal) | [a]-8.5 | 0 | -9.85 | 0 | -9.85 | -9.85 |
| | | | | | | |
| HJ5 - In-field grass areas to prevent erosion or run-off (baseline winter cereal) | [a]-8.5 | 0 | -10.23 | 0 | -10.23 | -10.23 |

[a] Represented by one case study farm

#### *4.2.2.2 Field corner management (EF1)*

Field corner management assumes a straight land use change to unfertilised grassland, and is similar to the buffer strip options except field corners are not assumed burdened with run-off from neighbouring cultivated land. Baseline crop yields within field corners are, in a similar manner to boundaries, subject to restrictions where buffer zones are stipulated for crop protection products. In addition, a proportion of the area may not be cropped due to access restrictions for machinery or are poor yielding due to compaction (from machinery turning), weeds due to poor spray targeting (difficulty with spray boom access), shading and waterlogging where drainage is poor. Entry into EF1 did not affect the management or crop yields outside of the option boundary (Area B).

#### *4.2.2.3 Grass buffer strips on intensive grassland (EE4, EE5 and EE6)/ 6m buffer strips on intensive grassland next to a watercourse (EE10)*

Stocking rates associated with intensive grassland may result in soil compaction, particularly where soils are vulnerable. This compaction may be removed upon reseeding every 5 years however will be present post year 1, especially where stock are grazed throughout the winter as was noted in the south east of England. Where intensive grassland was used primarily for supplementary feed production (silage or haylage) grazing of the aftermath occurs only during late summer after cutting. Intensive grassland typically receives supplementary N which, depending on slope gradient, risks surface run-off of N, although this is mitigated by the grass cover during the winter (Table 3.4). Although zero N is applied to the buffer strips themselves, the calculations assume burden with run-off from the neighbouring field, a proportion of which, subject to gradient and buffer strip width, intercepts the run-off and the N contained within it (Table 3.5). The following scenarios have been created:

1. Haylage + grazing of aftermath only (stock not assigned to land)

The decrease in haylage production was absorbed via the surplus sold off farm, it did not impact on feed provided to livestock on farm. No reduction in on-farm stocking rate resulted. A factor not previously included was the requirement of electricity to power an electric fence to separate grazing land from field buffer strips in order to exclude livestock.

#### *4.2.2.4 Floristically enhanced grass margin (HE10)*

The impact on GHG emissions of HE10 is similar in mechanism to the grass buffer strips on cultivated land described in section 4.2.2.1, for which two land use scenarios were identified:

1. Cultivated land (identical to option EE6 with additional species diversity)
2. Cultivated organic land previously within a Countryside Stewardship Agreement

None of the above scenarios were stated to alter management outside the ES option boundary (no on-farm displacement). Both case studies continued a previous Countryside Stewardship (CSS) Agreement for which an additional 2 m was entered into ES (2 m of the former CSS Agreement was absorbed by the required 2 m buffer under Cross Compliance). This arrangement assumed the creation of an equivalent 2 m buffer strip for the purpose of the calculations. For the organic rotation in (2) above the yield reduction was calculated as 100% of the potential crop yield since the impact of crop protection product buffer strips was not applicable. The rotation produced feed for on-farm consumption, mainly grass and clover with one year of spring oats. The loss of yield in (2) above did not require the import of additional feed from outside the farm boundary, it was absorbed by the existing feed surplus (silage land was not entered into ES specifically for this reason). The potential increase in floral species diversity (1 above) or inclusion of clover (2 above) in the stated mixtures may increase the SOC equilibrium above that of grass buffer strips alone (Table 3.9).

#### *4.2.2.5 Beetle banks (HF7)*

Beetle banks are located in the crop centre and remove crops at an assumed 100% yield potential unlike margins adjacent to field boundaries, or areas designated as 'field corners'. No alteration to management or yields outside the ES boundary (no on-farm displacement) was stated. Two scenarios have been created:

1. Winter cereal
2. Spring cereal

Some soil erosion and surface run-off mitigation is possible via beetle banks although this is at reduced rates due to the 2 m compared to a 6 m grass strip (Table 3.6). Their presence within central crop areas means run-off interception is potentially applicable to the length of the strip where implemented across the slope gradient.

#### *4.2.2.6 In-field grass areas to prevent erosion or run-off (HJ5)*

Similar to beetle banks, option HJ5 is present within more central parts of the field (100% yield potential loss) but specifically targets steep gradients where erosion and run-off are an issue. There was no stated alteration to management outside the ES boundary (no on-farm displacement) by farm managers.

Two scenarios have been created:

1. Winter cereal on high erosion risk land
2. Spring cereal on high erosion risk land

Areas of high percentage SOC and crops in receipt of higher N application rates will benefit from a greater overall GHG emissions reduction. Loss of SOC to soil erosion has been adjusted to the regional PESERA maximum of 4 to account for isolated within field areas of erosion risk not identified at the 1 km$^2$ resolution (JRC, 2002) but observed during farm visits.

#### *4.2.2.7 Restoration of species-rich, semi-natural grassland (HK7)*

The management of HLS option HK7 is specific to individual farms and potential baseline scenarios vary accordingly. The following scenarios have been devised:

1. Low input organic lowland hay meadows grazed rotationally by cattle and sheep with periodic intensive grazing during the spring by to control weeds
2. Semi-improved upland grassland grazed by sheep all year on organo-mineral (shallow high C containing) soils

On farm livestock numbers were not reduced in scenario 1 above due to the existing low input organic management and rotational grazing regime. Sheep may be grazed during the winter but are subject to a 6 month grazing plan in which stock do not remain in the same field beyond this period. Cattle are grazed during late spring as necessary to remove thistle. Compaction risk is lower at this time although the fine soil textures render the area potentially vulnerable when wet. Hay is cut during July.

Scenario 2 reduced within field sheep stocking rates and on-farm numbers overall (alternative grazing land off-farm was used) although a proportion of the livestock unit decrease was offset by the acquisition of cattle to diversify grazing structure and remove rush (*Juncus* species) on marshy grassland areas as part of the ES agreement. The grazing of the cattle on farm was not limited solely to the HK7 option area and the total equivalent cattle livestock units gained within HK7 was lower than that of the total sheep removed. Sheep remain grazed all year at lower stocking rates, cattle are not grazed during the winter or early spring. Feeding via troughs has been replaced with the spreading of feed supplement on the ground to prevent localised soil compaction and poaching. The small field size renders a greater proportion at risk to compaction (e.g. close to access areas such as gates) on a high risk naturally susceptible soil. A high SOC content within the soil however reduces this risk (Louwagie *et al*., 2008; Mudgal and Turbé, 2010). Compaction and surface run-off on the gradient will be reduced where compaction risk is decreased. Removal of compaction combined with the presence of marshy grassland within the area permits accumulation of additional SOC, this will be enhanced by the permitted natural silting of any previous drainage channels. The close proximity to a dwelling and enclosure of a small area renders it impractical to incorporate the field into a moorland restoration option. The reduction of livestock numbers, particularly during the winter, decreases N deposition onto wet SOC rich soils with potential for compaction. Manure is stored in covered piles and coincides with cool (below $10^{o}$C) mean temperatures for which methane emissions will be low, coupled with reduced leaching risk in a high risk (>800 mm) annual rainfall area. There was no specified requirement to artificially block drainage ditches as they were silting naturally. The calculations in Table 4.4 credit decreased $CO_2$ emissions (dependent on percent SOC) to HK7 where in this case study, it functions to prevent further drainage or repair of existing drains.

#### *4.2.2.8 Restoration of moorland (HL10) / Restoration of rough grazing for birds (HL8)*

Higher Level Stewardship management prescriptions are unique to individual farms. Baselines and scenarios have been constructed by aggregating the management of those case study farms assessed to devise three representative scenarios:

1. Semi-improved grassland stocking rates reduced to unimproved grassland stocking rates; proportional reduction of total on-farm livestock numbers (zero displacement)
2. Existing low input (recently converted organic) grassland (unimproved grassland equivalent stocking rates) on previously semi-improved grassland with no reduction in on-farm livestock numbers
3. Livestock numbers on moorland reduced by relocation to previously unimproved grassland through acquisition of additional land; conversion of unimproved grassland to semi-improved grassland (no change in on-farm stocking rates, displacement to existing unimproved grassland with lower SOC)

Scenario 1 maximises GHG reduction through a decrease in on-farm livestock numbers and the protection of high percentage SOC soils through removal of existing drainage (Case studies 9, 10, 13 and 14). Two case study farms had been previously within CSS agreements and these were continued through HLS. Although not applied to semi-improved grassland as standard, it was noted that a 20:20:20 NPK mix during early spring (equivalent to 30 kg N $ha^{-1}$) had been applied previously where deemed necessary in one case (albeit not annually). Locally steep gradients and rainfall in excess of 800 mm carries a high risk of surface run-off, especially where soil compaction has increased in response to increased livestock numbers (Louwagie *et al*., 2008; USDA, 2002). Surface run-off and loss of $NO_3^-$ is increased where supplementary N is applied and its removal via entry into ES decreases GHG emissions further.

In scenario 2 attempts had been made to improve the grassland with drainage but susceptibility to waterlogging and proliferation of rush *Juncus* species (recently acquired land applicable to Case study 12) resulted in poor quality grazing land not utilised by higher stocking rates associated with semi-improved grassland. Entry into HLS protects the high percent SOC soils. The GHG emissions reduction per ha is lower than scenario 1 due to the existing low baseline stocking rates. Emissions per livestock unit are greatly reduced where restoration eliminates $CO_2$ emissions from degraded organic soils (allocated to the baseline scenario livestock). Displacement risk is negligible and no reduction in on-farm livestock numbers occurs.

Scenario 3 (Case study 12) does not reduce or increase overall farm livestock numbers, stock on high SOC fields are absorbed by fields of lower percent SOC (this Case study farm had recently acquired additional land). Livestock numbers on-farm overall were not increased in scenario 3 but were relocated to other areas on the farm where grassland management was intensified from the existing unimproved grassland baselines. Emissions from soils were predicted to be reduced overall on account of lower percent SOC soils being present in these fields. Previously unimproved parcels of grassland are converted to semi-improved (typically are limed, receive P and K as supplementary nutrients, targeted control of weeds by topping) however these areas do not require drainage and are of lower percent SOC and are not allocated emissions from soil degradation. A baseline degraded high SOC soil emitting $CO_2$ is replaced with a soil of lower SOC but that is at equilibrium with no net $CO_2$ emissions.

Table 4.4. Change in GHG flux (t $CO_2$e $ha^{-1}$ $yr^{-1}$) including on-farm displacement for options HK7 (Restoration of species-rich, semi-natural grassland) and HL10 (Restoration of moorland) / HL8 (Restoration of rough grazing for birds). △Pr refers to livestock units.

| **Scenario** | **Equation 6** | | **Equation 8** | | **Equation 9** | **Equation 10** |
|---|---|---|---|---|---|---|
| | ^Pr Option Area A | ^Pr Option Area B | ^ GHG flux Area A | ^ GHG flux Area B | ^GHG flux$_{DISP}$ | GHG flux$_{DISS\ PROD}$ |
| HK7 (Restoration of species-rich, semi-natural grassland) (scenario 1) | 0 | 0 | 0 | 0 | 0 | 0 |
| HK7 (Restoration of species-rich, semi-natural grassland) (scenario 2) | -0.4 to -0.2 | 0 | -5.38 to -11.27 | 0 | -5.38 to -11.27 | -6.13 to -14.54 |
| | | | | | | |
| HL10 (Restoration of moorland) (scenario 1) baseline semi-improved grassland sheep upland LFA (zero N) | -0.9 to -0.6 | 0 | -9.57 to -13.28 | 0 | -9.57 to -13.28 | -5.71 to -20.48 |
| HL10 (Restoration of moorland) (scenario 2) baseline unimproved grassland equivalent | -0.2 to 0 | 0 | -5.42 to -11.35 | 0 | -5.42 to -11.35 | -64.23 to -123.45 |
| HL10 (Restoration of moorland) (scenario 3) baseline semi-improved grassland sheep + unimproved grassland below moorland line | -0.6 | 0.6 | -7.24 to -13.16 | 2.46 to 2.66 | -4.58 to -10.70 | -4.94 to -9.46 |

Note: HL10 scenario 1 includes case study farms previously in CSS Agreements for 10 years. The △Pr incorporates estimated (by the farm manager due to time elapsed) stocking rates before entry into the CSS Agreement, not the ES Agreement.

### 4.2.3 Habitat creation options and the scale of displacement

#### *4.2.3.1 Creation of woodland in Severely Disadvantaged Areas (HC9)*

Option HC9 permits the creation of small woodland areas of less than 1 ha. When implemented on peripheral unproductive areas which are components of larger fields subject to semi-improved or unimproved grassland management there is negligible impact on stocking rates. Three scenarios have been constructed:

1. Peripheral area of unimproved grassland with negligible impact on livestock numbers (absorbed by remaining grazing area within the field)
2. Low productivity 'field corner' area of semi-improved grassland with a proportion as existing plantation
3. Peripheral area located between two hedgerows subject to limited livestock access

Scenario 1 (Case study 14) implemented option HC9 in an existing area of low (unimproved grassland equivalent) stocking rates which, in combination with the small area removed from grazing access, resulted in no stated impact on livestock numbers on-farm and with no impact on management elsewhere (zero on-farm displacement). There is potential for additional biomass and SOC accumulation where trees replace grass.

Scenario 2 (Case study 12) utilised an area of apparent low productivity in a field corner bisected by a watercourse for woodland creation, where poor grass establishment was evident (poached bare earth) and vulnerable to surface run-off (the area was at the base of a slope and failed to intercept run-off from the remainder of the field entering the adjacent wetland area). Livestock had a tendency to congregate in this area due to the proximity of the water course and access area (gate and track). This is potentially problematic where there is a high natural soil susceptibility to compaction risk with damage to soil structure preventing rooting and grass growth although mitigated to a certain extent by the >13.1% SOC within the topsoil. Negligible accumulation of SOC was assumed due to limited biomass cover. The limited cover of grass also meant that the removal of this area from access to livestock had negligible impact on grazing availability. Part of the area allocated to HC9 was at risk to waterlogging during the winter (base of slope and area where field drains converged) and potentially increased $N_2O$ emissions from the deposition of congregated livestock onto high SOC soils. The waterlogged conditions which proliferate throughout the year corresponded to no predicted loss of $CO_2$ due to degraded high percent SOC soils although livestock congregation and loss of biomass meant at best, no further accumulation was possible. The remainder of the area was located on a raised bank with limited coverage by saplings of 10 – 15 years in age. The removal of unhealthy / non-native species and planting of additional broadleaved trees (approximately 80% of the area) has potential to increase biomass C within the area.

Scenario 3 (Case study 12) located HC9 between two hedgerows. Although livestock access was possible prior to entry into the agreement, evidence of access was negligible. No impact on livestock numbers resulted. Additional biomass and SOC accumulation has been calculated the same as for scenario 1.

#### *4.2.3.2 Creation of successional areas and scrub (HC17)*

One Case study farm (14) had entered into HC17, for which the following scenario was applicable:

1. Peripheral unimproved grassland with zero impact on livestock numbers (absorbed by remaining grazing area within the field)

No reduction in livestock numbers or management outside the option boundary was stated. The area was not subject to erosion or poaching therefore mitigation of emissions associated with these processes was not applicable. A potential increase in SOC and biomass C (Tables 3.8 and 3.9) has been calculated, scrub reaches an assumed equilibrium after 15 years.

Table 4.5. Change in GHG flux (t CO$_2$e ha$^{-1}$ yr$^{-1}$) including on-farm displacement for options HC9 - Creation of woodland in Severely Disadvantaged Areas and HC17 - Creation of successional areas and scrub. GHG flux$_{DISS}$ PROD is referred to as t CO$_2$e ha$^{-1}$ yr$^{-1}$.

| **Scenario** | ***Equation 6*** | | ***Equation 8*** | | ***Equation 9*** | ***Equation 10*** |
|---|---|---|---|---|---|---|
| | ^Pr Option Area A | ^Pr Option Area B | ^ GHG flux Area A | ^ GHG flux Area B | ^GHG flux$_{DISP}$ | GHG flux$_{DISS\ PROD}$ |
| HC9 - Creation of woodland in Severely Disadvantaged Areas (scenario 1) | 0 | 0 | -7.76 to -10.45 | 0 | -7.76 to -10.45 | -7.76 to -10.45 |
| HC9 - Creation of woodland in Severely Disadvantaged Areas (scenario 2) | 0 | 0 | -6.66 to -9.24 | 0 | -6.66 to -9.24 | -6.66 to -9.24 |
| HC9 - Creation of woodland in Severely Disadvantaged Areas (scenario 3) | 0 | 0 | -7.76 to -10.45 | 0 | -7.76 to -10.45 | -7.76 to -10.45 |
| | | | | | | |
| HC17 - Creation of successional areas and scrub | 0 | 0 | -4.68 | 0 | -4.68 | -4.68 |

## 5.0 Discussion

### 5.1 Options assumed to have no displacement

For the case study farms assessed, the assumption that there is no impact on yield (△ $P_r$ Area A) was verified for options EJ2 (Management of maize crops to reduce soil erosion) and HD3 (Low depth, non-inversion cultivation on archaeological features). The undersowing of spring cereals (EG1 and OG1 / OHG1) potentially experiences a reduction in yield (△ $P_r$ Area A) where winter sown crops are substituted with a spring crop. This was not applicable to the organic crops assessed. No change in management and GHG emissions (△ GHG flux Area B) or yields (△ $P_r$ Area B) were stated in other areas of the farm as a result of EJ2, HD3 or EG1 / OG1. A variable not previously taken into consideration, and of great relevance to EG1 and to a certain extent the crop proceeding EJ2, was temporal variability in weather patterns. Below average precipitation between February and April (2010 – 2012) was stated to reduce the yield of spring sown cereals proportionally greater relative to winter cereals. The substitution of a winter cereal with a spring cereal potentially has a greater impact on yield reduction (△ $P_r$ Area A) in response. The recent entry into agreements (2 years or less) of some options would however be an insufficient period of time to gauge with confidence the impact on yield of, for example, increased compaction associated with option HD3, an impact that may accumulate over a period of years (Knight *et al*., 2012) and would require monitoring over the duration of the agreement.

There was no stated impact on yield for maize crops grown under option EJ2 compared to previous baseline (pre-option) yields on any case study farm. Prolonged dry spring weather in the preceding 3 years was stated to result in poor establishment of spring sown crops on case study farms in Kent, notable on all assessed dominant soil textures (coarse, medium and fine). The option within EJ2 to establish an autumn sown crop after maize potentially reduces this risk where a spring crop is replaced in rotation with a winter crop. The substitution of a spring cereal with an autumn cereal immediately following the maize crop, particularly in areas vulnerable to lower annual precipitation, has potential to increase yields by a greater proportion within the rotation overall than a straight substitution of a spring with a winter cereal. Maize grown on fine soil textures were typically followed with winter cereals in the existing rotation due to inability to access fields with machinery in the spring (vulnerability to subsoil compaction when wet).

Emissions reductions were achieved by reducing surface run-off and the nitrate within, in combination with soil erosion and SOC. Some maize growing soils were predicted to contain 3.5 – 5.8% SOC (Jones *et al*., 2005), amongst the highest for cultivated land in the south-east. Prevention of erosion from these soils has a key role in mitigating agricultural GHG emissions (Jones *et al*., 2005; Kirkby *et al*., 2012; Panagos *et al*., 2012). Early maturing maize varieties allow earlier harvesting of the maize and drilling of the following winter cereal, for which earlier ground cover establishment potentially reduces the risk of water erosion of soil (Natural England, 2010a; USDA, 2002). Any additional cost incurred by the land manager for the purchase of such varieties could be met by ES payments. The full benefit of GHG emissions reduction potential for option EJ2, the undersowing of the maize crop, was not realised on case study farms with fine soil textures due to stated presence of blackgrass *Alopecurus myosuroides* Huds *Alopecurus agrestis* L. for which maize provides an opportunity within the crop rotation for its control. A potential loss of yield throughout the farm ($\triangle$ $P_r$ Areas A and B) may result from failure to utilise this opportunity. Crop yield loss due to blackgrass is estimated at 5% for less than five plants per $m^2$ (Storkey, 2006). A 5% yield loss for a winter wheat crop yielding potentially 9 t $ha^{-1}$ equates to nearly 0.5 t $ha^{-1}$, equivalent to approximately 0.4 t $CO_2$e in embedded GHG emissions.

A certain proportion of maize production was located on soils at high risk to compaction (Houšková and Montanarella., 2007), the removal of which is especially critical in these areas. The ES management specification for option EJ2 states '*remove areas of compaction*' which, on a high risk soil, will be applicable to the entire field. An undersown crop would, in all probability, be removed entirely upon completion of harvest, for which the option to follow with a winter crop would be of greatest benefit and indeed, was already undertaken on the farm. Heavy soils vulnerable to compaction tend to be drilled with winter crops as far as possible due to problems with accessing wet soils with machinery during the spring. The presence of a winter crop during the autumn and winter allows creation of a fine seedbed with good infiltration (Natural England, 2010a), although the earlier the drilling and establishment of the following winter crop, the greater the ground cover established preceding the winter and the lower the risk of water erosion.

Data for the scenarios created have been aggregated in order to standardise them although it is acknowledged that variation exists between farms. Differences in management may be subtle, but soil texture, local micro-climate (altitude and precipitation), field aspect and sowing date ultimately impact harvest date later in the year, and the date of establishment of the following crop and field management post maize harvest. Using scenario 2 (*Harvest by 1 October and establish an autumn-sown crop*) as an example, and two case study farms in close proximity geographically, one had successfully subsoiled and established a winter wheat crop following maize, the other had been unable to access the field post harvest due to prolonged heavy rainfall. Later drilling of the maize (for example by a few days) combined with a northern slope aspect possibly delayed maize maturity sufficiently to differentiate the harvest date between the two farms by 2 – 3 weeks (although both remained within the 1st October deadline). A finer soil texture that is also compacted prevents drainage and becomes waterlogged more rapidly (Louwagie *et al*., 2008; Machefert *et al*., 2002). This, in combination with higher than average rainfall during the late summer / early autumn ultimately prevented the drilling of a following winter cereal crop. Temporal changes in rainfall whereby above average rainfall occurs immediately preceding the harvest period also exerts an influence on the GHG mitigation potential of EJ2, albeit subject to variation between years. Difference in soil texture and compaction risk render well drained coarse soils less vulnerable than finer textured soils (Louwagie *et al*., 2008) with a potential increased window of opportunity to enter the field with machinery post harvest on the former. If scenario 3 (undersow the crop) had been utilised, the inability to access the field would not have been so problematic since the undersown crop would provide surface cover during the winter, albeit establishment may not have been optimal. Feasibility requires balance with *A. myosuroides* management and finer textures vulnerable to waterlogging earlier during the autumn are also more likely to have *A. myosuroides* present.

No stated change in management in crops that follow maize existed for the case study farms assessed. The decision to drill a spring or winter crop after maize is a balance of yield opportunity between the two crops. A winter cereal drilled later in the autumn will typically decrease in potential yield and margin to a point where the balance shifts in favour of a spring crop. Warmer mean temperatures, such as those in the south-east, offer greater opportunity for a later drilled autumn crop to be economically viable than a spring crop. The area also has some of the highest solar irradiation for the maize growing region within England (higher than, for example, East Anglia) (Huld *et al*., 2012) and therefore crops are more likely to reach maturity during September and permit a subsequent winter cereal under EJ2. Further north, where solar irradiation decreases, the substitution of a spring cereal with a winter cereal in response to EJ2 may be more frequent but would require verification. Maize crops, where previously followed by a spring crop due to the later harvest date but where a winter cereal was now grown, offer the opportunity to increase yields in the following crop (increased $\triangle P_r$ Area B). Where there is risk of lower precipitation during the spring, the $\triangle P_r$ Area B has potential to be greater.

The undersowing of spring cereals on non-organic land substituted a winter cereal with a spring cereal although it must be emphasised that this option, and the discussion that follows, is limited to a single case study farm. The substitution of a winter cereal crop with a spring cereal crop with option EG1 reduces yield by up to yield 30% (AgroBusiness Consultants, 2012; Nix, 2012) depending on cereal variety and soil conditions. It was noted by a number of farm managers in the south east of England that the occurrence of dry springs in recent years had greatly increased the difference in yields between the two. Winter sown crops were able to establish a more robust root system before the onset of limited rainfall. In contrast, spring sown crops were recently germinated and growth was greatly delayed. It would be reasonable to assume that this yield reduction would be more extreme on soils with low soil water availability (coarse soils) (Panagos *et al*., 2012), areas of lower rainfall (north-east Kent) (EDIT, 2012) and warmer air temperatures to increase evapo-transpiration (Kent) (Figures 2.1 and 2.2). This assumption was supported in part by the assertion of farm managers in Northumberland who stated they had not experienced yield losses due to lack of precipitation during the spring for the same years in question. Particular parts of the chosen case study regions are potentially more vulnerable to yield loss from option EG1 implementation. Where the crop yield is reduced or worse, fails, the GHG emissions per unit of output will be considerable. A subsequent cultivation will be required with limited biomass return (roots and stubble), similar to fallow areas where there is a risk of loss of SOC. The baseline yield stated by the farm manager were within the upper range of those given by Nix (2012). A worse case loss of yield in one particular case study would be up to 9 t ha$^{-1}$ for an assumed failure of spring cereal establishment having replaced a winter cereal crop, significantly greater than the predicted 2 t ha$^{-1}$ reduction for an average yielding winter cereal (Nix, 2012) compared to a spring cereal.

The OG1 / OHG1 agreements on organic land typically did not alter the crop rotation specifically in response to entry into ES but established a grass / clover ley via undersowing the spring cereal as opposed to post harvest of the spring cereal. Options OG1 on organic land were stated by farm managers not to impact on production since undersown spring crops already existed within the rotation although on OHLS land, reduced seed rates were a requisite of the management agreement on one case study farm as a component of option OS2. Seed rates on organic land may be higher than their non-organic counterparts as it is a technique employed to reduce weeds (Lampkin, 2004). Potential yield reductions from lower seed rates (where applicable) may be compensated by increased weed control derived from the undersown mix although this will depend on baseline weed conditions and history. On coarse soils where residual N is lower (Defra, 2010) weed infestation may be potentially lower than a finer textured soil (Tzilivakis *et al*., 2005ab) to which a lower seed rate may have less of an impact on yields.

Undersowing the spring cereal crop on organic land potentially removes one set of operations associated with crop establishment. The undersown mixture continues to develop after harvest of the spring cereal crop and forms a temporary grass / clover ley. This would have normally been sown as a separate set of operation after spring crop harvest. It was stated by one farm manager that establishment of the undersown crop was not always successful, possibly due to their presence on north facing slopes with greater shading once the crop had established. Solar irradiation declines with progression north (Huld *et al*., 2012). Undersown crops on northern aspect slopes in Northumberland would, by this rationale, be expected to be more vulnerable to poor establishment although this was not found to be the case. Corresponding evidence within the literature directly applicable to aspect and undersown grass / clover leys is sparse, however the production of certain horticultural products (for example asparagus) exploit differences in microclimate (i.e. north or south facing slopes) to delay growth and extend harvest periods. Failure to establish the undersown crop on organic land requires that an additional set of seedbed preparation and drilling operations be undertaken. On non-organic land the substitution of N fixed by clover is assumed removed with potential for application of N where patchy establishment results in N from both supplementary N application and N fixation by clover. This would then be vulnerable to environmental loss if not utilised by the crop.

There was no stated impact on yield for option HD3 in Northumberland, the rotation required modification to remove non-drillable crops (in this example, potatoes) but yields of the remainder (cereals and oilseed rape) did not change. No case studies were present in the south-east although one farm utilised minimum tillage, albeit not as option HD3, for which there was no stated change in yield, although it was acknowledged that differences in weather conditions and the recent adoption of the technique into the farms management meant it could not be stated with certainty. The influence of erratic weather (prolonged dry springs and wet summers) influenced crop yields potentially beyond the shift in management. Published literature refers to greater water retention in soils that are minimum tilled compared to deeper ploughing (Louwagie *et al*., 2008). This would suggest minimum tillage may have a greater positive impact on crop yields on soils of low available water capacity and in regions of lower annual precipitation. Mitigation of the impact of prolonged seasonal dry weather would be applicable to these soils in particular. Below average spring rainfall in the south-east render this option potentially more important for its ability to improve soil water retention although the longer term impact on soil compaction and crop root penetration (Knight *et al*., 2012) requires consideration. Fine soil textures where the AWC is higher but the risk of compaction is greater, may not benefit, especially if compaction results and prevents deeper root penetration.

### 5.2 Options that remove part of a field from production and the extent of displacement

On-farm displacement of production was not identified for the priority options that remove a proportion of the field from crop or livestock production. On cultivated land, variation was attributed to their potential impact on baseline crop yields within the option area, which was subject to farm specific variables and differences in location within the field (edge or centre). Options to implement grass buffer strips adjacent to farm woodlands (directly north or north-east) removed areas where crop yields were negligible in the outer 3 – 4 m but had received in large, standard crop management in the outer 6 m (subject to stipulated buffer width requirements for certain agro-chemicals on non-organic land). Where buffer strips are adjacent to watercourses, restrictions on the application of crop protection products results in potentially decreased yields in the outer crop areas also. Again, entry of these areas into ES did not reduce yields by 100% of the yield potential but of variable proportions (variable baseline yields) depending on the products applied, the method (type of sprayer and spray nozzle) and the properties of the watercourse (width, presence of water) which all impacted on the buffer strip width under LERAPS approval (UK Pesticides Guide, 2012). Options implemented in central crop areas (beetle banks and within field grass areas) were not subject to these restrictions and full potential yield penalties were incurred.

The restoration of species rich grassland (HK7) was undertaken in two contrasting areas: a cooler upland climate with high annual precipitation (EDIT, 2012) and high C containing soils (Jones *et al*., 2005) in the north-east of England compared to a warmer lowland climate of moderate SOC and annual precipitation in the south east of England. On farm displacement of production did not occur in either case study. The impact on yield in response to entry into HLS differed because of differences in baseline management scenarios. A semi-improved grassland baseline but where grazing land was of poor quality to sheep due to dominance of *Juncus* species decreased livestock numbers, although this was not as great as if the grazing land had been of a higher quality. The other baseline was existing low input organic grassland grazed rotationally for which there was no requirement to adjust livestock numbers. Removal of the *Juncus* species by cattle and restoration to species rich upland hay meadow will ultimately improve the quality of grazing land and permit increased hay yield for winter feed purposes. The small enclosed nature of the field and its close proximity to the farm dwelling meant that it was impractical for it to be entered into the moorland restoration options discussed in the next paragraph. The natural silting up of the existing limited drainage combined with the cooler temperatures and high precipitation should be sufficient to reduce and ultimately prevent emission of $CO_2$ from degraded organic soils.

The restoration of moorland, subject to alternate areas of unimproved grassland existing on-farm, was the only option where there was potential to intensify management outside the ES option boundary and contribute to on-farm displacement. This was in the form of unimproved grassland below the moorland line receiving supplementary nutrients and weed control to enable grazing of higher stocking rates. Substitution of drained high percentage SOC soil with a lower percentage SOC soil where drainage was not required as semi-improved grassland has a net reduction in GHG emissions overall. The presence of finer clay soil textures potentially results in higher susceptibility to soil compaction (Houšková and Montanarella, 2007) which is a potential negative of increased management on these areas. The case study farm was moderate-high with respect to natural susceptibility to compaction. This, in combination with rainfall above 800 mm per annum may cause high surface run-off. Where supplementary N is applied to the soil surface, increased emission of $N_2O$ is a risk, although application of N to semi-improved grassland was not undertaken as standard procedure. It should be noted that the areas of moorland undergoing restoration by ES were restricted to the moorland edge.

### 5.3 Habitat creation options and the scale of displacement

No on-farm displacement of production was evident for the priority habitat creation options under consideration. This was mainly due to the small size of the areas entered into HLS. Both options and case study farms utilised peripheral farm areas where inputs and existing livestock numbers were already low or access was limited. Combined with the small area entered, this did not require that farm stocking levels be altered.

## 6.0. Conclusions

For the majority of priority options evaluated, there was no evidence of on-farm displacement. Declines in crop yield were evident where options removed agricultural production or substituted winter with spring sown cereals. The magnitude of this yield loss was influenced by local site climatic variables (precipitation and temporal variation in), soils (texture and available water content) and proximity to field boundaries, watercourses and woodland.

The GHG mitigation potential of options that maintain agricultural production are maximised where yield reduction is also minimised. For option EJ2 a following winter cereal crop achieves this objective, potentially facilitated by the use of earlier maturing varieties, especially at higher altitudes or with progression north. Options that replace winter cereals with undersown spring cereals appear to be more vulnerable to greater yield reduction and increased GHG emissions per unit of output where there is a greater risk of prolonged below average spring rainfall, and lower available soil water (for example on coarse soils). Areas of south-east England for example may be particularly vulnerable, and taking this risk into account when implementing these options would be advisable.

Options that remove a proportion of a field from production potentially maximise GHG mitigation with appropriate positioning (for example where there is surface run-off) or where yield reduction may be lower (adjacent to / north of woodlands, adjacent to watercourses, areas of poor drainage). Where restoration of moorland habitats occurs on degraded carbon rich soils, the displacement of livestock onto mineral soils of lower SOC, subject to available land and adherence to recommendations, would be potentially beneficial assuming $CO_2$ emissions from the degraded baseline soils are then mitigated.

## 7.0. References

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