Capturing Cropland and Grassland Management Impacts on Soil Carbon in the UK LULUCF Inventory

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Summary for Policy Makers

This project aimed to identify the extent to which emissions due to changes in Soil Organic Carbon (SOC) stocks arising from Cropland and Grassland/Grazing Land management can be incorporated into the UK's Land Use, Land Use Change and Forestry (LULUCF) inventory. The UK is required to develop such reporting to meet international commitments for reductions in greenhouse gas emissions.

Developing frameworks for reporting these emissions would also allow assessment of the scope for Cropland and Grassland management to increase SOC stocks as greenhouse gas mitigation measures.

Key management activities were identified which might affect SOC stocks. For Cropland these were crop type, crop residue returns, manure and fertiliser inputs and tillage regime. For Grassland the key management activities were Grassland type, residue returns, manure and fertiliser inputs, rotation pattern and erosion. Drainage of organic soils was not considered in this project.

A literature review carried out as part of the project concluded that tillage reduction cannot be considered a reliable management option to increase the SOC content of UK soils. However increasing crop residue returns and increasing inputs of manure and fertiliser could increase SOC stock although the SOC stock increases resulting from manure and fertiliser inputs could be outweighed by increases in nitrous oxide emissions and the risk of nitrate run-off.

The review found that increasing crop yields through increased fertilisation and improved crop rotation could increase the annual input of crop residues and root exudate to soils and hence increase SOC on low fertility soils. Manure additions resulted in greater C sequestration than the addition of equivalent amounts of N as mineral fertiliser and the effect lasted longer. However, increasing inputs of nitrogen from fertiliser or manure risk increasing N_2O emissions which could negate any increases in SOC stock.

IPCC default stock change factors were judged to be inappropriate for the UK, based on expert opinion and the literature review findings. Therefore the project used the Daily DayCent and Landscape DNDC models to attempt to estimate stock change factors for Cropland management activities under UK conditions. Although based on a very limited dataset, outputs from the model suggested that the effect of Cropland management activities under UK conditions might be less than implied by the IPCC stock change factors. Tillage reduction was found to have little effect on SOC stocks. Increasing manure and crop residue inputs increased SOC stocks, with manure inputs being particularly effective.

A framework for reporting SOC stock changes resulting from Cropland management was developed, and used to assess mitigation options. Overall the impact of Cropland Management on SOC is likely to be very small compared to other activities in the LULUCF inventory such as land use change. The most effective mitigation option was converting Cropland from annual tillage crops to perennial crops, fallow and set aside. However given the need for food production there is limited scope for such change. Increasing manure, fertiliser and crop residue inputs gave smaller increases in SOC stocks, but practical considerations limit the scope of these actions.

A lack of field data on the effect of Grassland improvement on SOC stocks was identified as a knowledge gap. The literature review suggested that intensification could increase SOC stocks under pasture on mineral soils. However, expert opinion suggested that this might not be the case for rough grazing on organo-mineral soils, where intensification might lead to SOC loss. This lack of data meant that it was not possible to calibrate or validate models to estimate UK specific stock change factors for Grassland. As the IPCC stock change factors were judged to be inappropriate to UK conditions, assessment of the mitigation potential of Grassland management using these factors was not carried out to avoid presenting potentially misleading results. Suggested strategies for filling these knowledge gaps are outlined in the report.

Attempts to assess grass/crop rotation patterns across the UK using data from the Integrated Administration and Control System (IACS) used to handle Common Agricultural Policy (CAP) payments were hampered by difficulties in obtaining access to the data. However land use change matrices were generated for England and Wales, and used to map areas of change. Subject to data availability, this approach could be used in future inventories to give a better representation of the effect of rotation patterns on SOC stocks.

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1 Introduction

1.1 Purpose of project

The UK is required to report emissions of greenhouse gas emissions and removals from Land Use, Land Use Change and Forestry (LULUCF) activities for carbon budgets to meet international commitments under the Kyoto Protocol (KP), UN Framework Convention on Climate Change (UNFCCC) and under the European Union Monitoring Mechanism (EUMM). Reporting is also required to meet domestic obligations under the UK Climate Change Act, the Climate Change (Scotland) Act and emissions reduction strategies set up the Welsh Government and Northern Ireland Assembly.

To date the focus of LULUCF reporting has been emissions from Land Use Change. The effects of most land management practices on soil and biomass carbon stocks have not been reported[1]. For the Second KP Commitment Period (COP2) reporting on emissions and removals from Cropland and Grazing Land management will remain optional, but European Regulation EU529/2013 phases in mandatory accounting for Grassland management and Cropland management by Member States under the European Union Monitoring Mechanism.

This project aimed to identify the extent to which emissions due to changes in soil carbon stocks arising from Cropland and Grassland/Grazing Land management can be incorporated into the UK's LULUCF inventory. The project assessed whether the default stock change factors for land management activities given in the 2006 IPCC guidance were appropriate for UK conditions, and attempted to model more appropriate stock change factors where necessary.

The project has already reported on a literature review of emissions and removals from Cropland and Grassland Management (Buckingham et al, 2013) and on Other Countries' Approaches to Reporting Emissions and Removals from these activities (Watterson et al, 2013).

This report briefly summarises the findings of these two reports before moving on to look at key management activities identified on Cropland and Grassland in the UK; the activity data available for each of these activities; the development of stock change factors applicable to the UK and the use of IACS data to derive Grassland/Cropland rotation patterns. It then assesses what the mitigation potential of key management activities is.

1.2 Identification of Key Management Activities

The KP and UNFCCC both give frameworks for considering emissions and removals LULUCF activities. While there are similarities between the two systems there are also some notable differences. In the context of this project the main difference in between Grazing Land Management as defined by KP and Grassland Management as defined by UNFCCC.

[1] Emissions from agricultural liming have been reported in the LULUCF inventory. These emissions arise from the loss of CO_2 from the carbonate in lime, not from the effect of increased pH on soil carbon stocks. Emissions from wildfires have also been reported, but these are emissions from unmanaged fires, rather than fires used as a land management tool e.g for heather management.

The UNFCCC land use classification uses six land use classes: Forest, Cropland, Grassland, Wetland, Settlement and Other Land. For most land use classes the KP definitions align with UNFCCC, but there are differences between KP Grazing Land and UNFCCC Grassland. Grazing land is defined as land used for livestock production where management is aimed at manipulating the amount and type of vegetation and livestock produced. UNFCCC defines Grassland more widely as "rangelands and pasture land that are not considered Cropland. It also includes systems with woody vegetation and other non-grass vegetation such as herbs and brushes that fall below the threshold values used in the Forest Land category. The category also includes all grassland from wild lands to recreational areas as well as agricultural and silvi-pastural systems, consistent with national definitions." (IPCC, 2006)

While both KP Grazing Land Management and UNFCCC Grassland Management include management activities on agricultural land which supports livestock such as cattle, sheep and pigs, UNFCCC Grassland Management captures some additional activities for example heather management on grouse moors.

The KP land use classification scheme is shown schematically in Figure 1.1.

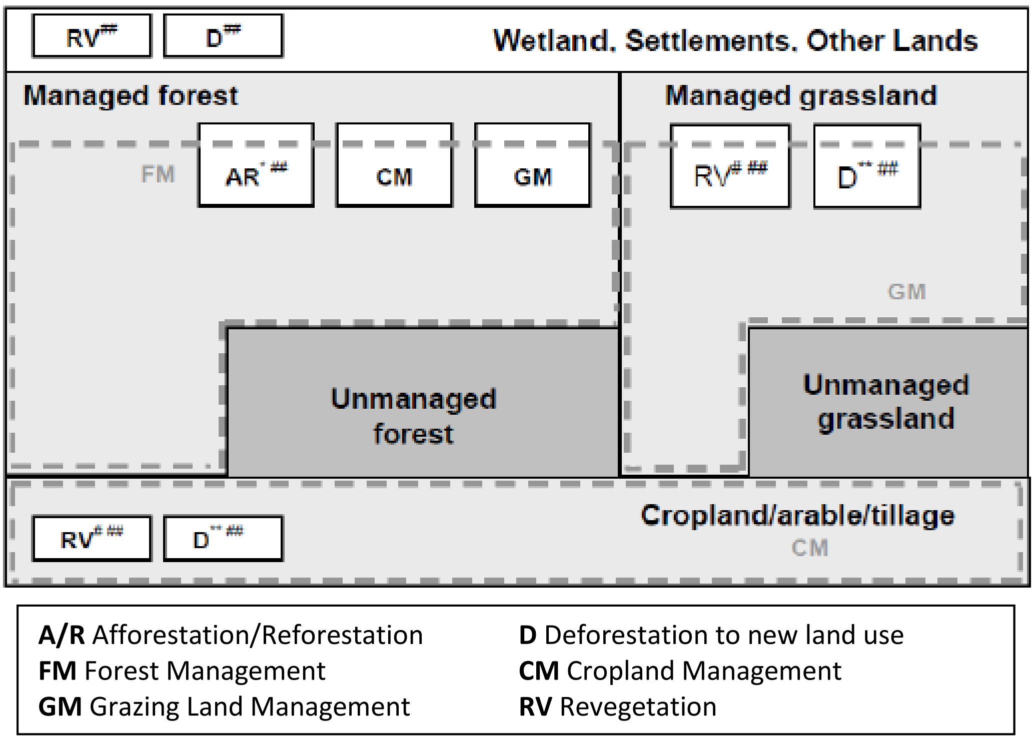

Figure 1.1 Kyoto Protocol land classification scheme

1.2.1 Cropland management

Key management activities for Cropland in the UK which had the potential to affect soil carbon stocks were identified using expert judgement by the project team. Land management activities such as managed burning and liming which were judged to have only small effects on soil carbon stocks were not included. (Emissions from managed burning currently reported in the LULUCF inventory are emissions from burnt biomass rather than from soil carbon loss, and emissions from liming are from release of carbon dioxide from the carbonate in lime rather than from any consequential change in soil carbon stocks).

Key Cropland management activities:

- Crop type: residue inputs will depend on crop type, the duration of crop cover will vary for the different crop types, and soil disturbance will be less frequent under perennial crops than annual.
- Manure inputs which add carbon to soil directly, and also increase N content which promotes crop growth in N deficient areas, and hence can increase carbon returns to soil via root exudates and residues.
- Fertiliser inputs increase nutrient content of nutrient depleted soils which promotes crop growth and increases carbon returns to soil via root exudates and residues.
- Crop residue returned to the soil. This depends on the crop grown and the harvesting/ residue removal regime.
- Tillage regime: conventional mouldboard plough cultivation compared to reduced and non-tillage techniques
- Drainage of organic soils (already included in the UK LULUCF inventory for Cropland in England)
- Grass-Crop rotation pattern. Grassland has higher SOC stocks than Cropland. Therefore including grass in a rotation would be expected to increase SOC stocks. However this effect is likely to be more marked for rotations where several years under grass are followed by one year under a crop than for land which is planted with a crop in most years, but is occasionally used for grass.
- Cover crops. Bare soil may increase loss of SOC through erosion and respiration. Maintaining soil cover by use of winter-sown crops or a specific cover crop could help to preserve SOC stocks.

1.2.2 Grassland Management

Key Grassland Management activities:

- Grassland type: improved Grassland, rough grazing and Grassland with woody shrub (e.g. heather moorland). Woody Grassland which is managed (e.g. by burning heather to promoted grouse habitat), but not grazed is included in UNFCCC reporting, but will not be considered as Grazing Land for KP reporting.
- Residue returns
- Manure inputs. As described above can increase soil carbon directly and because N inputs increase crop growth and hence residue returns
- N inputs from fertiliser, manure and legume mixes
- Rotation pattern. Agricultural census data divides Grassland to grass less than five years old and grass more than five years old. UNFCCC guidance states that rotational grass should be considered as Cropland. Grass less than five years old falls into this category. However, in some areas the rotation may be predominantly grass, with occasional crops. In these areas grass recorded as being more than five years old may be subject to regular, if infrequent disturbance. In addition some improved grassland is ploughed and reseeded on a regular

basis. This may be shown on census returns as grassland more than five years old even though the soil has been subject to periodic disturbance and equilibrium soil carbon stocks may not have been achieved.

- Drainage and rewetting of organic soils
- Erosion. Although strictly speaking a response to management UNFCCC guidance treats the extent of erosion as a management practice for the purpose of calculating change in SOC stocks.

1.3 Literature Review – Main Findings

A review of literature on the effect of Grassland and Cropland management on SOC stocks has already been published as part of this project (Buckingham et al, 2013). This assessment of literature on the effects of Grassland and Cropland management on soil carbon was hampered by the limited number of studies applicable to UK soil and climate conditions. What literature was available tended to give inconsistent results on the effects of management practices because they were carried out on different soil types, in different climate zones or used different experimental approaches

Many studies only considered carbon stock changes in the top 30 cm, rather than the full depth affected by management practices. This can give misleading results. A further complication was that not all studies included bulk density measurements, and so it was not possible in all cases to assess whether reported change was due to real change in SOC stocks or was simply an effect of change in bulk density. In addition, not all of the results reported in the literature were from long term studies making it unclear how long the reported rates of change in SOC stocks persist.

Findings from studies comparing the effect of zero-tillage and conventional tillage on soil organic carbon (SOC) concentrations were difficult to interpret because of inconsistent sampling depths and lack of bulk density information. However, they did not generally indicate an increase in SOC sequestration as a result of zero tillage when these factors were taken into consideration. While studies which only considered the top 30 cm suggested that tillage reduction could increase SOC stocks, this effect was less clear in studies which sampled to lower depths. This suggests that tillage reduction may change the distribution of SOC within the soil profile, with more carbon remaining near the surface under a reduced tillage regime, but tillage reduction may in not lead to an overall increase in SOC stocks. Therefore tillage reduction cannot be considered a reliable management option to increase the SOC content of UK soils.

The review found that increasing crop yields through increased fertilisation and improved crop rotation could increase the annual input of crop residues and root exudates to soils and hence increase SOC on low fertility soils. Manure additions resulted in greater C sequestration than the addition of equivalent amounts of N as mineral fertiliser and the effect lasted longer. However, increasing inputs of nitrogen from fertiliser or manure risk increasing N_2O emissions which could negate any increases in SOC stock.

Leaving crop residues in the field was found to increase SOC content in several studies. Studies on perennial energy grasses suggest that they have the potential for storing a significant quantity of SOC.

Grassland soils generally store large amounts of carbon. However, the uncertainties on the effects which management has on SOC stocks are large. In mineral soils under improved Grassland, fertilisation is generally considered to enhance carbon storage due to enhanced plant productivity and residue and root inputs to soil. Enhancing species diversity and, in particular, introducing new deep-rooted grasses with higher productivity into the species mix has been shown to increase SOC contents, particularly on low-productivity pastures.

On lowland Grassland, cutting and grazing have several interacting effects on soil carbon stocks. Moderate stocking density can increase carbon sequestration (from low baselines) but urine inputs can raise pH which may mobilise soil organic matter throughout the soil profiles. Higher stocking densities tend to reduce pasture production and residue returns, and therefore can have a negative impact on SOC storage.

Decomposition rates in many upland soils are constrained by acidity. Increases in pH due to liming or reduced sulphate deposition consistently lead to increased productivity, but also accelerated C turnover. Intensification of nutrient-poor grasslands developed on organic soils can therefore lead to large C losses. Grassland C sequestration per unit area may be favoured by extensive management provided that nutrients are not limiting. Inorganic fertiliser additions in all studies on grassland gave changes in carbon stocks of -21 to 27 t C/ha.

In all studies, positive changes in grassland soil C stocks (0.7 to 15 t C/ha) were brought about through slurry or manure applications.

Overall the literature review concluded that there are limited opportunities to increase the SOC content of UK soils. The review suggested that the most effective option would be increasing inputs of organic manures to soils, particularly those with lower SOC contents. However, the applicability of this option is limited by the availability of farmyard manure and other suitable organic wastes, and by the need to balance manure inputs with N requirements to minimise nitrous oxide emissions and nitrate run-off. Better targeting of organic manures to soils with low SOC content could increase SOC stocks while making better use of N already applied. This would not increase emissions of N_2O, but would incur some CO_2 emissions from transporting manure from the location it was produced at to the application site.

1.4 International Comparison - Main Findings

The LULUCF National Inventory Reports (NIRs) of 11 countries with similar agricultural sectors to the UK were reviewed to establish with land management practices were reported under Cropland and Grassland (Watterson et al, 2013).

Canada, Denmark, Portugal and Spain reported under KP on Cropland Management, and Denmark and Portugal reported under KP on Grazing Land Management. More countries reported on emissions and removals by Grassland and Cropland under UNFCCC reporting. Activities included for each country reviewed are shown in Appendix 1

The NIRs reviewed contained less detail than hoped on the methodologies used. Several countries commented on the difficulty of obtaining the activity data on historical land management practices which is needed to complete the inventory for years past years and to include the effect of historical changes in land management to which soils are still responding.

1.5 IPCC Cropland and Grassland Reporting Guidance

The IPPC 2006 Guidelines (IPCC 2006) on reporting emissions from Agriculture, Forestry and Other Land Uses (AFOLU) will replace the 2003 Guidelines on LULUCF reporting (IPCC 2003) for the 1990 – 2013 inventory. The AFOLU guidance give a framework and stock change factors for Tier 1 reporting of emissions from Cropland and Grassland management.

For mineral soils, change in carbon stocks is given by Equation 1.1.

Equation 1.1

ANNUAL CHANGE IN ORGANIC CARBON STOCKS IN MINERAL SOILS

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$

$$SOC = \sum_{c,s,i} \left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i} \right)$$

(Note: T is used in place of D in this equation if T is ≥ 20 years, see note below)

Where

$\Delta C_{mineral}$ = the annual change in carbon stocks in mineral soils (tC /y)

SOC_0 = SOC stock in the more recent year (tC)

$SOC_{(0-T)}$ = SOC stock at the start of the time period (tC)

SOC_0 and SOC $_{(0-T)}$ are calculated using the SOC equation in the box

T = time period (yr)

D = Time dependence of stock change factors.

c*, s and i* represent the climate zones, soil types and land management systems considered.

SOC_{REF} is the reference carbon stock (t C/ha)

F_{LU} = stock change factor for a particular land use

F_{MG} = stock change factor for the management regime

F_I = stock change factor for organic matter inputs

A = area of land under a given soil, climate and management regime (ha)

The IPCC 2006 Guidelines gives default stock change factors which can be used in the absence of more specific factors. The default factors for moist temperate areas such as the UK are shown in Table 1.1 for Cropland and Table 1.2 for Grassland.

Table 1.1 IPCC default Cropland stock change factors

Activity	Stock change factor
F_{lu} Long term cultivated	0.69
F_{lu} Perennial crop	1.0
F_{lu} Set Aside	0.82
F_{mg} Tillage – Full	1.0
F_{mg} Tillage – Reduced	1.08
F_{mg} Tillage – No till	1.15
F_i Low input	0.92
F_i Medium input	1.0
F_i High input	1.11
F_i High input with manure	1.44

Table 1.2 IPCC default Grassland stock change factors

Activity	Stock change factor
F_{lu} All Grassland types	1.0
F_{mg} Nominal management (non-degraded)	1.0
F_{mg} Moderately degraded	0.95
F_{mg} Severely degraded	0.7
F_{mg} Improved	1.14
F_i Medium input, improved	1.0
F_i High input, improved	1.11

2 Modelling Stock change factors

Although the 2006 IPCC Guidelines gives default stock change factors for key land management activities, these were developed using broad climatic zones. While the factors for moist temperature zone could be used for the UK, development of factors reflecting UK conditions would allow more accurate reporting and avoid creating perverse incentives towards management practices which are not beneficial under UK conditions. This was considered to be important given that UK soils have relatively high SOC contents.

Two process based soil models were used to derive stock change factors for Cropland management activities in the UK, the DailyDayCent run by Aberdeen University and Landscape DNDC run by Scotland's Rural College. Both models need field data for calibration and validation. For Cropland the best data for doing this come from the long-term field sites at the Rothamsted research station. These were used as the main basis of modelling, but stock change factors were also modelled at four other soil monitoring sites maintained by Defra to give an indication of the variability of stock change factors across the UK and the model was also run using climate data for a more northerly site at Crichton near Dumfries.

There were insufficient field data on long term on changes in SOC stocks as a result of management practices to enable modelling of stock change factors for Grassland management practices in the UK. However, as stated above IPCC default stock change factors may not be applicable to UK soils. Using these stock change factors could give a misleading picture of the effect of management practices on soil carbon and lead to incentives for practices do not actually benefit SOC stocks. There is therefore a need to obtain better field measurement of SOC stocks under grassland to inform work to model UK-relevant stock change factors for Grassland management practices.

2.1 DailyDayCent modelling of mitigation options on croplands in UK

The objective of the work presented in this section is to determine the mitigation potentials for croplands in UK using computer models, to complement the estimates from the literature. We performed computer simulations with the biogeochemical model DailyDayCent (del Grosso et al., 2001; del Grosso et al., 2006) to predict changes in soil organic carbon (SOC) for different modifications of management practice.

DailyDayCent (DDC) is a biogeochemical model that based on previous versions DAYCENT (Parton et al., 2001; del Grosso et al., 2001, 2006) and CENTURY (Parton et al., 1987, 1988; Parton and Rasmussen, 1994). The model simulates plant growth, water balance, nutrient cycling and soil organic matter SOM) dynamics on a daily time step. Site and soil specific data, daily maximum and minimum temperature and precipitation data are required as input data to run the model. DDC simulates carbon dynamics for agricultural lands, grasslands, forests and savannas, including nitrogen, phosphorous and sulphur dynamics, although in this study only the carbon and nitrogen cycles are considered.

Plant growth is simulated by potential growth, dependent on temperature with modifications by water or nutrient limitations, and the assimilated carbon is allocated to above ground and below ground biomass. The SOM module distributes soil organic matter (SOM) into three different pools: a fast active pool (with a turn over time of 1-3months), a slow active pool (with a turn over time of 10-50 years) and a passive pool (with a turn over time of 400-4000 years). Decomposition rates follow first order kinetics and are modified by pH, soil temperature and soil water content. The simulation of SOM dynamics is restricted to the top 20 cm of the soil.

Water balance is simulated for the entire soil depth, with a tipping bucket module to determine the soil water content. The model contains default values for different tillage options, which affect the decomposition rates of the different SOC pools. The dates for the different management practices are provided as input parameters in a schedule file.

For the study presented here there was little information about historic and recent SOM values for the experimental sites. Therefore, a spin up of 1500-2000 years was used to get equilibrium for the soil organic carbon pools at the beginning of the study period (2000). The spin up for the Rothamsted test site was shorter (70 years), because there were more data of measured SOM.

DDC and DAYCENT are calibrated on a wide range of crops (Manies et al., 2000; del Grosso et al., 2001; del Grosso et al., 2005; Stehfest, 2005) and validated at a number of sites measuring greenhouse gas emissions (e.g. Frolking et al., 1998; del Grosso et al., 2001), including an evaluation of N_2O emissions at nine UK experimental sites (Fitton et al., 2014 – in review). The model is already tested and used for simulations on croplands (Stehfest, 2005; Adler et al., 2007, Sansoulet et al. 2014), grasslands (Yeluripati et al., 2009; Abdalla et al., 2010) and forests (van Oijen et al., 2011; Cameron et al., 2012). In this study the settings and parameters used in other studies on croplands in Europe (NitroEurope and CarboExtreme) were adopted.

The model used weather data (daily time steps), soil data and specific site information to determine, beside the SOM dynamics, plant growth, greenhouse gas emissions and the water balance.

Winter wheat sites were chosen to remove crop type as a variable affecting mitigation potential. In a first approach the mitigation potential was determined for a long term test site at Rothamsted, with a winter wheat monoculture and detailed data from 1975 to 2009.

In a second approach, the changes in SOC stocks were simulated on four experimental sites in UK, located in Betley, Boxworth, Middleton and Terrington, with data sets of one to three years (all with winter wheat monocultures). The study period for the second approach was 2001-2005. Weather data were filled using duplicates of the available data.

The management practice on the Rothamsted site was changed so that simulations reflect the best agronomic practice in the UK (see Table 2.1). For both approaches, two simulation runs per option were made: one as a baseline run with current management (with assumptions of best practice where specific details were not available), and another one with all conditions the same, except for the application of the mitigation option. This enabled the impact of the mitigation option to be determined. Based on the two simulation results the mitigation potential was determined as a stock change factor (SCF in tC/ha/y) calculated by the equation:

$$SCF = 1 + \frac{(SOC_{mitigation} - SOC_{baseline})}{(SOC_{mitigation}\ x\ time\ )} \qquad \text{(Equation 2.1)}$$

Where $SOC_{mitigation}$ is the mean annual change in SOC with management including the mitigation options, $SOC_{baseline}$ is the mean annual change in SOC with the baseline settings, and time as the number of years since the mitigation practice was first implemented (see also section 1.5). Additionally, on the Rothamsted site, the impact of other factors were tested by different set ups, modifying the initial SOC content (10 g/kg and 20 g/kg), different climate data (Rothamsted climate and climate data of a test site in Crichton, UK) and different soils (beside the sandy silt loam of the Rothamsted site, a sandy loam of the Betley test site, and a silty clay loam of the test site in Terrington (Appendix 2.1).

Table 2.1: Summary of the management practise of the baseline and the different tested mitigation options in the first Daily DayCent approach on the Rothamsted test site. The management kept constant over the study period (1975-2009).

	Fertiliser [kgN/ha]	Residue removal [%]	Manure [kgN/ha]	Tillage
Baseline	1 X 50, 2 X 80	85	no	ploughing
Scenario 1	1 X 50, 2 X 80	70	no	ploughing
Scenario 2	1 X 50, 2 X 80	50	no	ploughing
Scenario 3	1 X 50, 2 X 80	85	no	no
Scenario 4	1 X 50, 2 X 80	85	no	low-intensity
Scenario 5	1 X 25, 2 X 40	85	no	ploughing
Scenario 6	1 X 100, 2 X 120	85	no	ploughing
Scenario 7	1 X 33, 2 X 80	85	no	ploughing
Scenario 8	1 X 33, 2 X 80	85	170	ploughing
Scenario 9	1 X 41.4, 2 X 80	85	no	ploughing
Scenario 10	1 X 41.5, 2 X 80	85	85	ploughing

2.1.1 DailyDayCent Results

For both approaches and all modifications, the mitigation options considered were reduced tillage, manure application instead of fertiliser application and less residue removal.

For tillage reduction, the literature does not supply sufficient information on site characteristics for models to be run which are directly comparable with published studies. This study used two sets of default values in the model to represent two different tillage methods and the zero tillage option.

The values use for the baseline and mitigation runs (first approach) are summarized in table 2.1. In contrast to the simulations on the Rothamsted site, the baseline settings and mitigation options are slightly modified in the second approach. All of the four experimental sites have different management (manure application on Betley and Middleton and application of mineral fertiliser on Boxworth and Terrington), different climate data and also different soils (Appendix 2.1). In the second approach, the baseline already includes 50% residue removal, and therefore, the mitigation options are 30% residue removal and 0% residue removal. The baseline values of the second approach are summarized in Table 2.2. The mitigation options are modified as mentioned above and according to the baseline fertiliser/manure application rates.

Table 2.2: The baseline settings for the management practise on the four experimental sites of the Daily DayCent second approach.

	Fertiliser [kg/ha]	Residue removal [%]	Manure [kg/ha]	Tillage	Initial SOC [t/ha]
Betley	no	50	2300	ploughing	38.2
Boxworth	1 X 40, 2 X 60	50	No	ploughing	54.3
Middleton	no	50	500	ploughing	71.1
Terington	variable*	50	No	ploughing	47.7

*the fertiliser application rates changed during the study period

This study analyses computer simulation results, and measurements are used only to ensure realistic conditions at the start of the runs (i.e. for model initialisation). The results are compared with those obtained using the Landscape DNDC model to provide a check on the output. The results for the first approach (Rothamsted) show the strongest positive effect on SOC for the replacement of fertiliser by manure, while modifications of tillage show the lowest impact (figure 2.1 and figure 2.2). Manure contains organic carbon, which is directly applied on the soil and has a direct impact on SOC. The crop availability of N applied in fertiliser as well as its degradation and leaching are lower than for the mineral fertiliser application. Yields may be enhanced due to increases in other nutrients provided by manures and therefore the residue return may increase, providing an additional indirect positive impact on SOC.

The mitigation option of less residue removal shows the second most effective impact on SOC and enables a carbon gain of up to 0.4 t C/ha/y (for only 50 % residue removal instead of 85 % removal in the baseline scenario at Rothamsted; figure 2.3). In contrast to these two options, an increase of the yield by applying more fertiliser shows a much smaller effect on SOC (about 1/6 to the maximum of the manure option and about a quarter of the maximum effect of the residue removal option). Similar effects are seen for the low-tillage and no-tillage options. In the simulation results, neither tillage method (no tillage and less intensive tillage) deliver an appreciable increase in SOC.

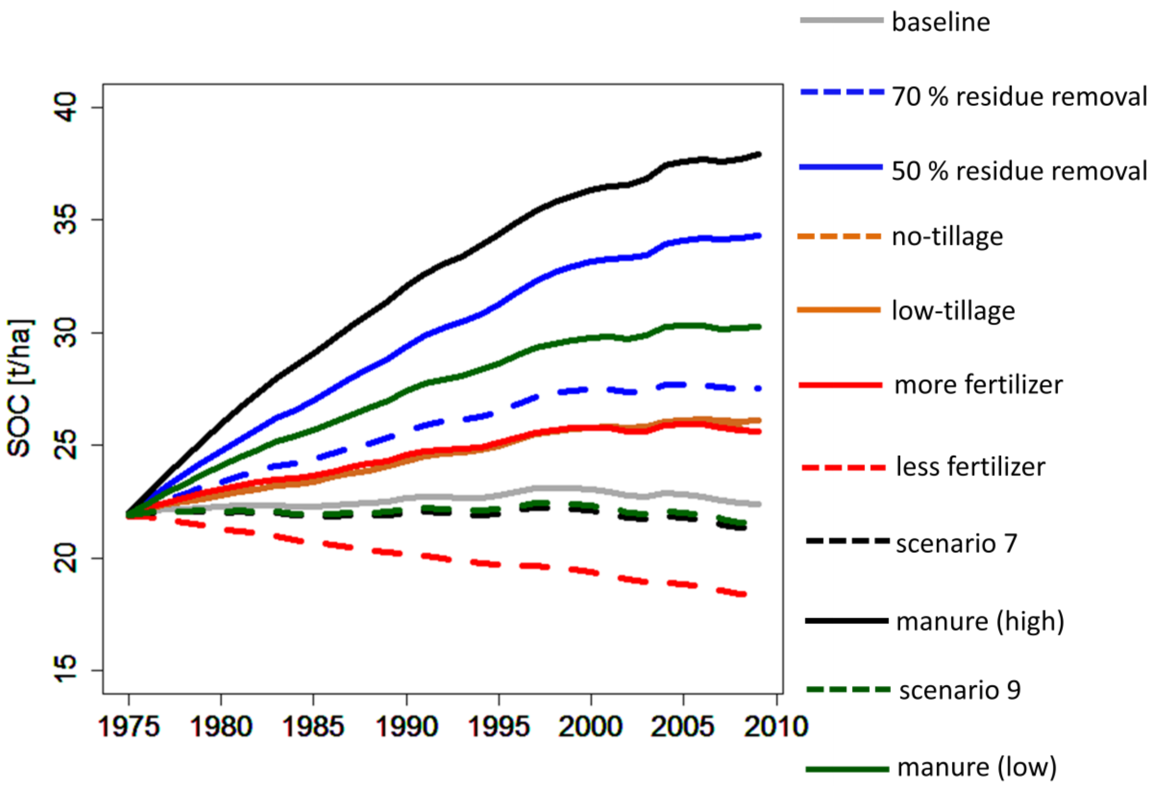

Figure 2.1: The SOC values for the different scenarios of the first approach. (10g/ha initial SOC). The scenarios below the baseline are the option with less fertiliser application (dark brown) and the two baselines for the manure application scenario that consider also less fertiliser application (scenario 7 and 9). The different scenarios are summarized in Table 2.1.

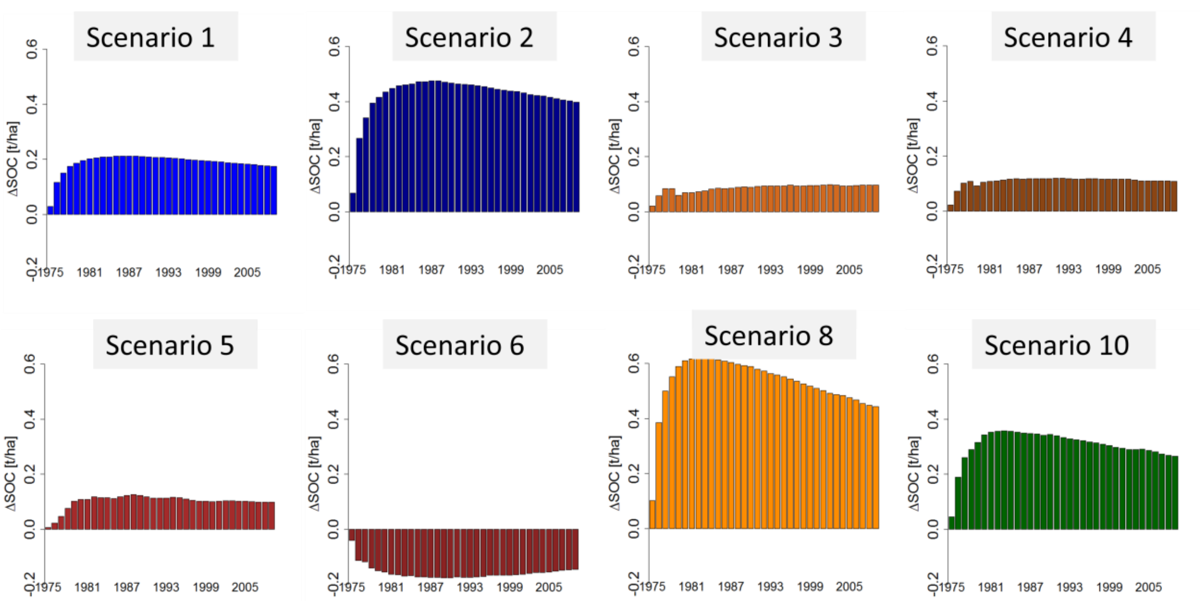

Figure 2.2: Mitigation potential based on simulation results using soil and climate data of Rothamsted according to the different scenarios in Table 2.1. The figure shows the annual change in SOC stock.

The effects of changes in management may depend on several other factors like weather conditions, soil type or the initial amount of SOC, which were also tested on the Rothamsted test site. The higher initial SOC is important in terms of mitigation potential only for tillage changes. In contrast to the simulations with lower SOC, the simulation results with 20 g/kg SOC (instead of 10 g/kg) show a mitigation potential about 10 % higher for less intensive tillage and no tillage (figure 2.3).

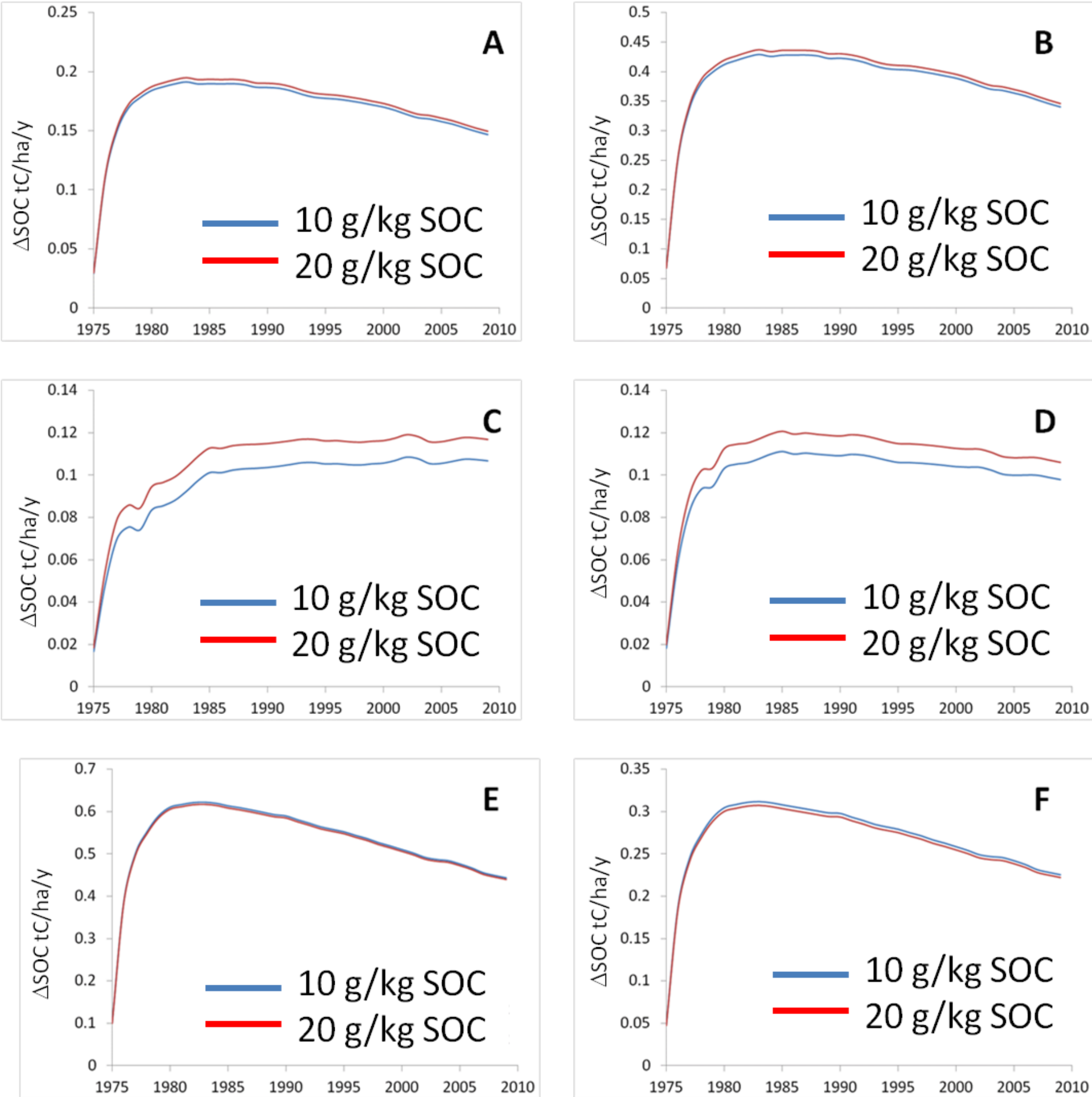

Figure 2.3: Comparison of the different mitigation options for 10 g/kg (blue lines) and 20 g/kg (red lines) initial SOC (A: 30 % residue removal, B: 50 % residue removal, C: no-tillage, D: low-tillage, E: manure application (high), F: manure application (low)).

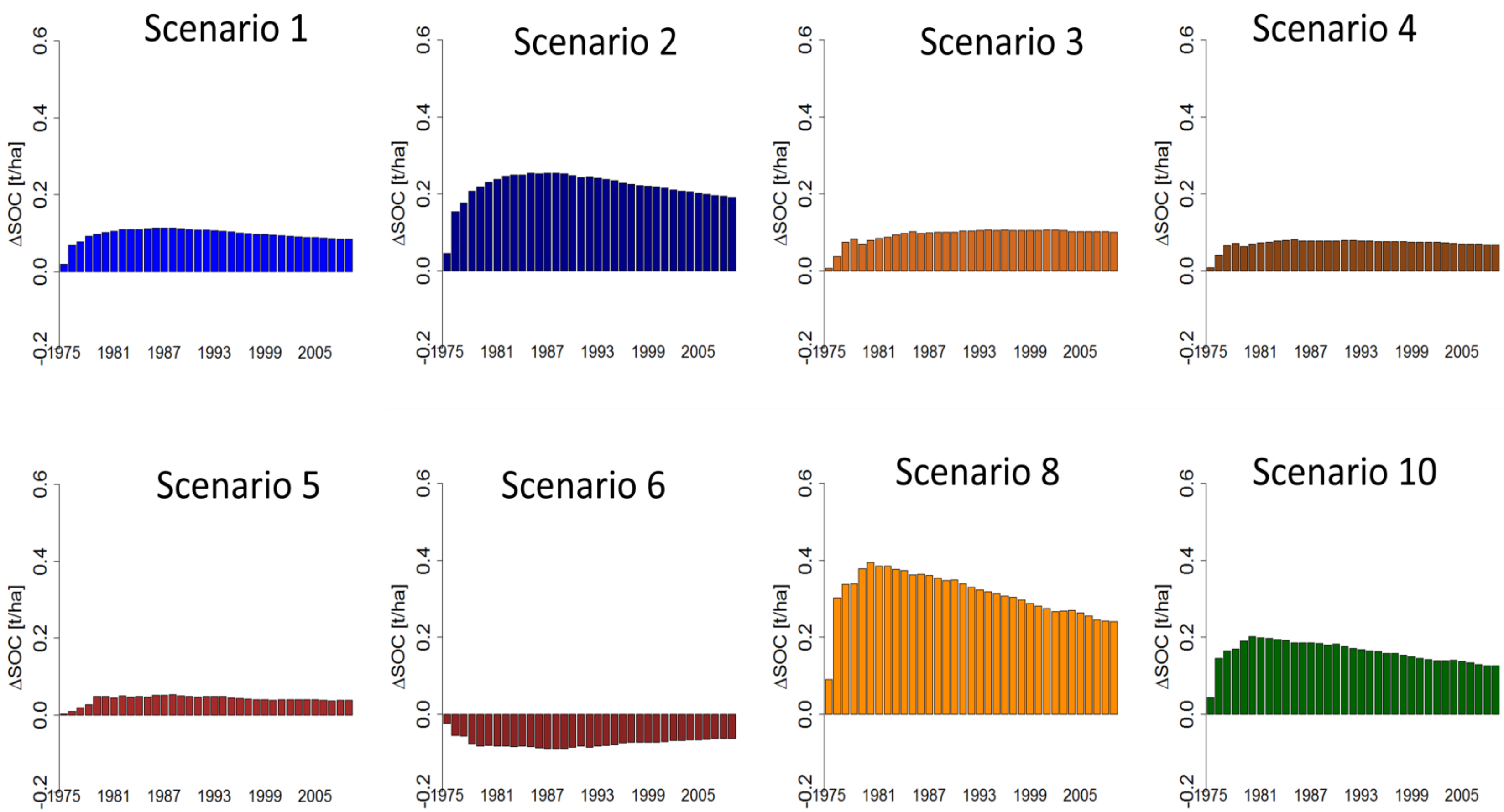

Figure 2.4: Mitigation potential based on simulation results using the climate data of Rothamsted with the soil data of Betley (Appendix 2.1) according to the different scenarios in Table 2.1. The figure shows annual change in SOC stock.

While the initial SOC shows an effect for one mitigation option, the simulation results with a different set of climate data show virtually no differences for the mitigation options. Simulations with climate data where temperature was increased by one degree showed no effect on the different mitigation options (data not shown here). In contrast, there are big differences for the results of simulations with different soil types. While the more sandy soil, with low clay content showed 1/3 less mitigation potential for the manure and residue removal options (Figures 2.4 and 2.5), the mitigation potential for the more clayey soil was slightly higher than the results of the simulations with the Rothamsted soil type (Figure 2.6).

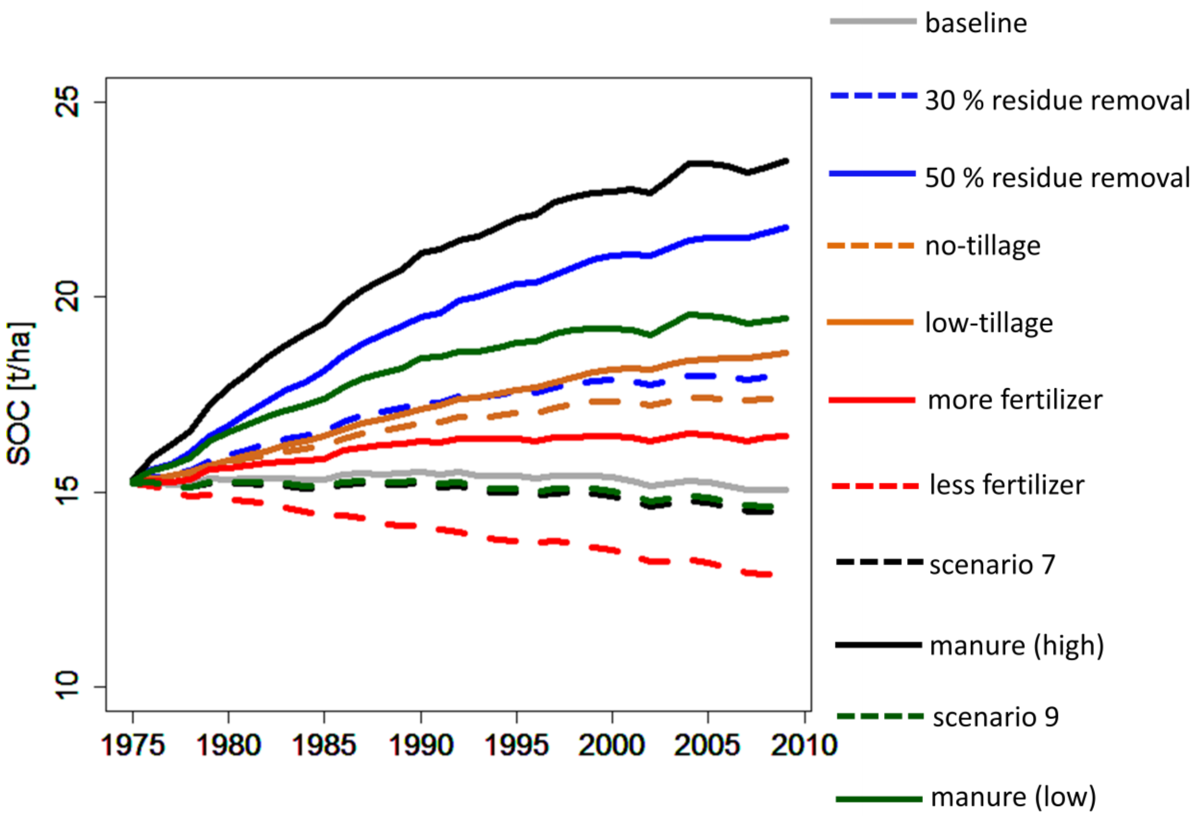

Figure 2.5: The SOC values for the different scenarios with the soil of the Betley test site (Appendix 2.1). The scenarios below the baseline are the option with less fertiliser application (red dashes) and the two baselines for the manure application scenario that consider also less fertiliser application (scenarios 7 and 9).

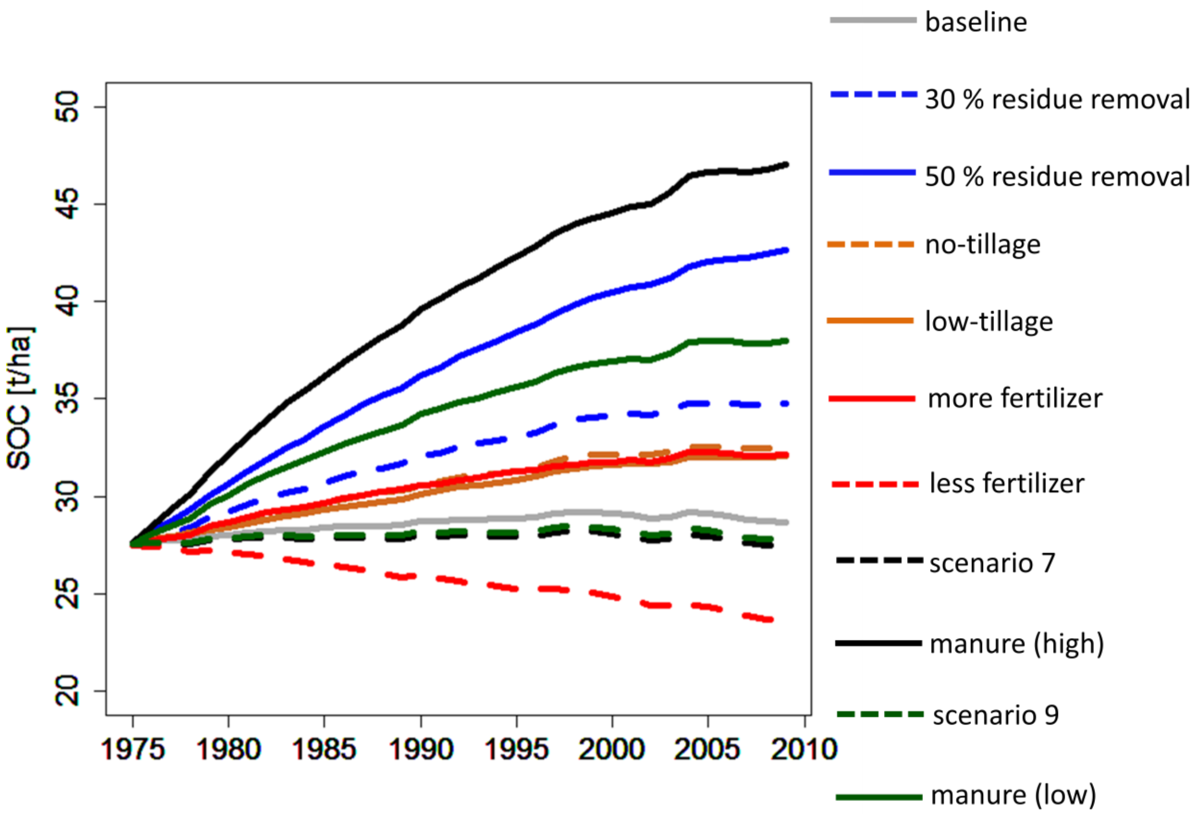

Figure 2.6: The SOC values for the different scenarios with the soil of the Terrington test site. The scenarios below the baseline are the option with less fertiliser application (red dashes) and the two baselines for the manure application scenario that consider also less fertiliser application (scenarios 7 and 9).

The simulation results of the second approach support the findings of the first approach (Appendix 2.2). Because of the different residue management, this mitigation option shows a stronger impact on SOC than manure application increase or replacement of mineral fertiliser by manure, but the general order of the other mitigation options is the same. The potential (averaged over all experimental sites) for reduced or zero tillage (0.11 t C/ha/y) and the manure option (0.46 t C/ha/y) is about the same as in the first approach.

The IPCC Fourth Assessment Report (Smith et al., 2007; Smith et al., 2008) provides mitigation potentials for different climate regions and different management options. According to the IPCC report changes of reduced or zero tillage or residue removal enable an increase of SOC of about 0.14 t C/ha/y (with a range of 0 – 0.28 t C/ha/y) and for changes in the fertiliser/manure application of about 0.24 t C/ha/y (with a range of -0.14 – 0.34 t C/ha/y) in the cool moist climate zone. In comparison to these values, the simulation results of this study show about average values for tillage (0.11 t C/ha/y in the first and second approach), values at the high end of the range for residue removal (0.34 t C/ha/y in the first approach), and values above the maximum for the manure options (0.44 t C/ha/y in the first approach / 0.46 t C/ha/y in the second approach) over 35 years in the first approach and over 5 years in the second approach. The results of the second approach show a maximum mitigation potential for residue removal of 0.46 t C/ha/y, but this is based on no removal of residues (in comparison to a 50 % removal baseline). This assumption shows the maximum potential, but is unrealistic. The more realistic scenario (only 30 % removal rather than 50%) shows an increase of 0.19 t C/ha/y, which is above average, but still below the maximum values.

The effects of mitigation can also be described as an annual factor for the change of SOC over a fixed period. This factor represents the increase of SOC over the considered period per year (so that starting SOC multiplied by the factor multiplied by the number of years gives the SOC at the end of the considered period). Based on the limited data availability it is not possible to provide these factors for UK, but Table 2.3 shows the factors for the simulation results of the 4 experimental sites (Betley, Boxworth, Middleton and Terrington) and the Rothamsted test site.

A high manure application has the highest impact on the SOC resulting in a simulated increase in SOC of up to 2.9 % of the starting SOC stock per year on the Rothamsted site, while changes of residue management show a maximum increase of 2.1 % per year. Tillage options show an increase of 0.4-0.7 % per year for the top 20cm only but this may not be representative of the whole soil profile, where SOC decreases deeper in the soil may wholly or partly negate gains in the surface layers. A reduction of fertiliser (in this study the amount is halved), results in a decrease of SOC of about 0.2-0.5 % per year.

The results for most mitigation options show higher factors over shorter time periods, since SOC change is maximal early in a transition and steadily declines to zero as the soil approaches a new equilibrium. The values presented here should not be used as stock change factors as they are based on too few sites and have not been adequately validated against measurements. Nevertheless, they are indicative of the direction of change and relative magnitude, so are useful for comparing mitigation measures, given that data from the literature is too sparse to derive these values directly from measurements. More definitive factors could be derived for the UK by running the model for a wider range of soil / climate / management combinations, but that was not possible given the resource available.

Table 2.3 shows stock change factors for average annual change in SOC during the study period with the different mitigation options for the test sites considered. The factors are normalised over the period (change divided by the number of years) and consider the periods of 5 years (the maximum period for the experimental sites), 20 years (this is the standard period for an SOC change used in the IPCC tier 1 method) and 35 years (maximum period in this study). The “5 year experimental site” column shows the average factor for the 4 experimental sites with the standard deviation (except for the mitigation options for fertiliser that show only the average of the two fertiliser sites). The three columns (5, 20, 35 years) of the Rothamsted test site show the factors of the simulation results where SOC is assumed to be 10 g/kg of soil.

Table 2.3 Stock change factors for average annual change in SOC during the study period with the different mitigation options for the test sites considered.

Treatment	Experimental sites* 5 years	Rothamsted 5 years	Rothamsted 20 years	Rothamsted 35 years	IPCC default stock change factor
30%/70% residue removal**	1.006 ± 0.003	1.011	1.010	1.007	1.00[a]
0%/50% residue removal**	1.011 ± 0.004	1.021	1.020	1.016	1.11[b]
no tillage	1.004 ± 0.002	1.006	1.006	1.005	1.15
low tillage	1.004 ± 0.002	1.007	1.007	1.005	1.08
double fertiliser	1.011 ± 0.005***	1.008	1.007	1.005	
half fertiliser	0.998 ± 0.001***	0.995	0.995	0.995	
double manure	1.011 ± 0.004	1.029	1.027	1.021	1.44[c]
half manure	1.001 ± 0.005	1.016	1.014	1.011	

* Average for the Betley, Boxworth, Middleton and Terrington sites
**the first number for the experimental sites, the second for the Rothamsted sites
***the average for the experimental sites based on only two test sites
a – default factor for medium residue input
b – default factor for high residue input
c - default factor for high residue input plus manure.

The results shown in Table 2.3 give some indication of the variation in stock change factors between sites, but do not include any estimate of uncertainty arising from the limited data used to calibrate the DDC model. This is likely to be much higher than the modelled between site variation in stock change factors. Table 2.9 compares stock change factors generated by DDC with those from Landscape DNDC.

The effect of no tillage and reduced tillage is less than indicated by the IPCC default factors for all sites and all timescales. The effect of decreasing residue removal is also less than suggested by the IPCC default factors. While it may be less valid to compare the double manure result with the IPCC factor for high residue returns plus manure, the modelled effect of this large increase in manure input is much less than the IPCC default factor even if multiplied by the modelled factor for low residue removal (high residue return).

The modelling and literature review results are in agreement on the efficacy of the mitigation options. Tillage reduction to low- or zero-tillage showed varying results depending on several abiotic factors as summarised in the literature review. One of the most crucial parameters is the soil depth that is considered, which influences the results and also the qualitative trend. The conclusion of the literature review suggests that tillage as a not an appropriate mitigation option to increase SOC, and shows small to negligible effects. The simulation results of DailyDayCent show an increase of SOC by 0.11 t C/ha/y, but the results are for simulations of the top 20 cm of the soil only. Such increases in the top 20cm agree with many of the field measurements in the literature, but there are often compensatory losses deeper in the profile. Whilst the model suggests a modest increase in the topsoil, estimates for deeper soil layers would be needed to assess whether tillage modification is a viable option for mitigation – with the literature suggesting that this is not the case.

The nitrogen dynamics of the four experimental sites (Betley, Boxworth, Middleton and Terrington) are analysed in Fitton et al. (2014 – in review) and the results show a range of 0.52 to 2.5 kg N_2O-N/ha/y for the measurements and a range of 0.8 to 2.2 kg N_2O-N/ha/y. The data do not show a clear trend of higher or lower nitrogen emissions according to fertiliser or manure application type, but emissions increase with fertilisation rate. There are no measurements available for carbon emissions and also historic information about influencing factors are missing for validation data for net ecosystem exchange (NEE). The simulation results of DailyDayCent for the two experimental sites with fertiliser application show a small carbon sink, while the other two experimental sites show a neutral NEE balance (Middleton) or tend to be a source (Betley). These values are based on the study assumptions of 50 % residues left on the field. If only 15 % of residues were left on the field and 85 % removed from the system, all experimental sites would be carbon sources. For more solid estimates additional measurements are necessary.

Despite the limitations by simple assumptions, model structure and data availability; the results can be used as estimates for order of magnitude and direction of change in SOC achieved by the different mitigation options. Extremes such special soils (e.g. organic soils) or weather (e.g. extreme dry years) are not considered in this study. Limited data availability do not allow us to represent all croplands and managements in UK (limitation in e.g. the crop type or fertiliser management). However, the simulations considered a typical cropland site and provide useful information about the relative impacts of the different mitigation options. To get more representative results, and better coverage of the entire range of extremes, more data are necessary, especially more data over longer periods (long term experiments). This would be achievable with additional resource and future projects should address this gap in their objectives. Given the lack of clear literature results, modelled estimates using well validated models such as DailyDayCent are the only viable way to estimate soil carbon change factors.

In conclusion, according to simulations on UK cropland sites using the DailyDayCent model, stock change factors for SOC in the top 20 cm of soil for tillage reduction are similar to the average values reported in the meta-analysis of Smith et al. (2008) for the cool-moist climate zone, but less than the IPCC default values. As stated above, DailyDayCent only considers the top 20 cm of soil. Increases in SOC stock to this depth as a result of tillage reduction are likely to be counteracted by reduction in the SOC stock of deeper soils, so the overall effect is likely to be small.

The stock change factors for residue removal, depending on the approach, are close to the maximum values reported in Smith et al. (2008), or even exceeded the range, but are less than the IPCC default values.

The replacement of fertiliser by manure also shows a stronger impact on SOC than the maximum values suggested in Smith et al. (2008). The IPCC AFOLU guidelines do not give factors stock change factors for fertiliser inputs, although it is included indirectly through its effect on residue returns.

Climate had no appreciable impact on the mitigation potentials, but extreme weather situations were not considered in these tests. The initial SOC value affects the impacts of tillage, but did not affect the mitigation potentials of residue removal or fertiliser/manure management. The simplified test with different soil types showed a strong impact on all mitigation options. The approach used did not allow for a detailed analysis of the main drivers for this effect, but there is a general trend of stronger positive effects for higher clay contents and lower sand contents in the soil.

The study shows that the maximum mitigation potential of residue removal and fertiliser replacement by manure on SOC in UK may be higher than those suggested by the meta-analysis of Smith et al. (2008) for the whole cool-moist climatic zone, but are less than suggested by the IPCC default stock change factors.

2.2 Landscape DNDC modelling of mitigation options on croplands in UK

Where limited field data is available for model validation, confidence in modelled results can be increased by running more than one soil process model and comparing results. To provide a check on results obtained with the DailyDayCent model, the mitigation potential of management options was also modelled for the Rothamsted plots using the Landscape DNDC model.

LandscapeDNDC (LDNDC) is a process-based model for simulating biosphere-atmosphere-hydrosphere exchange and processes at site and regional scales. The LandscapeDNDC is a new framework that is based on the biogeochemical site scale model De-Nitrification De-Composition (Li 2001) and incorporates a series of new features with regard to process descriptions, model structure and data functionality (Haas et al 2013). The model divides ecosystems into six substrates (canopy air chemistry, microclimate, physiology, water cycle, vegetation structure, and soil biogeochemistry) and provides alternative modules dealing with these substrates (Haas et al 2013) as shown in Figure 2.7.

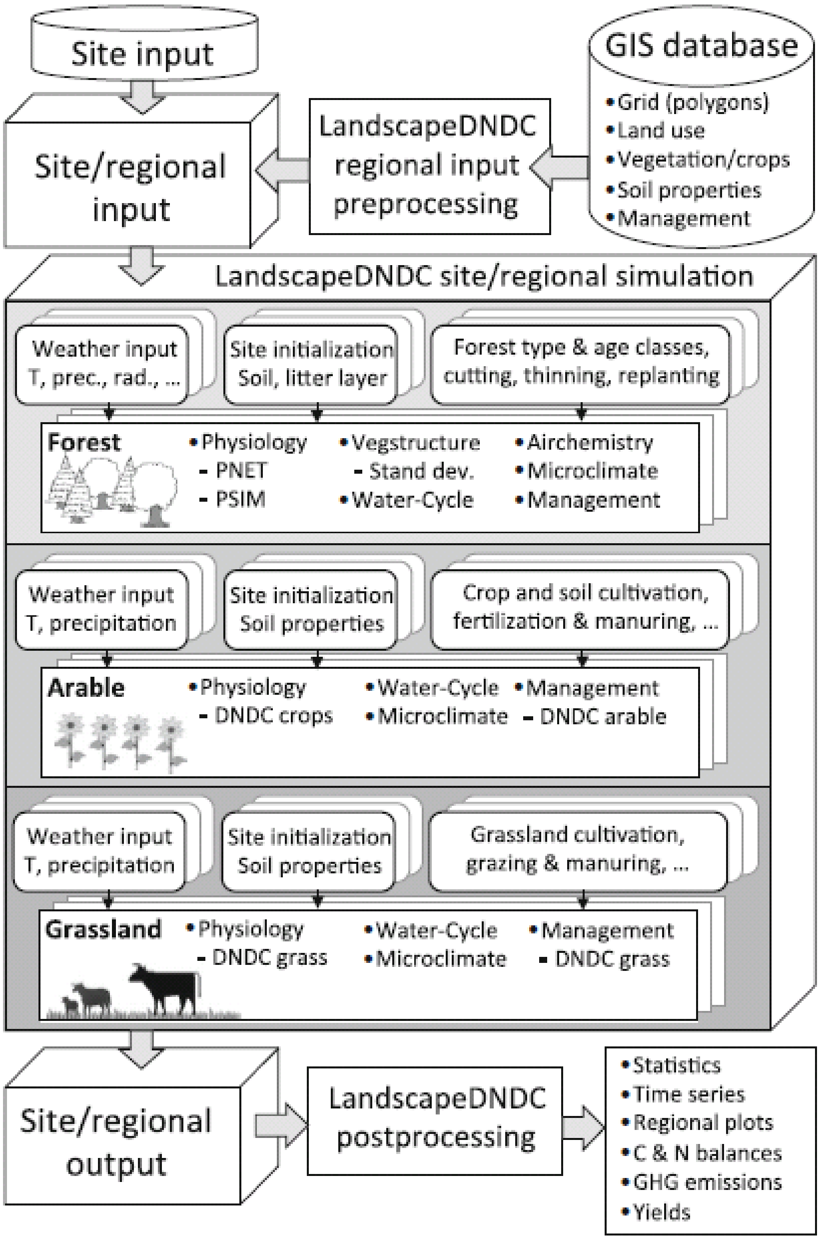

Figure 2.7. LandscapeDNDC data flow for site/regional applications.

LandscapeDNDC creates a forest, arable or grassland ecosystem type for each grid cell associated with different site properties and climate and management input data. During the simulation, Landscape DNDC can treat each grid cell with a different configuration. The model results are collected per time step and per grid cell and streamed into regional output files. Running LandscapeDNDC for one grid cell equals a site simulation (Haas *et al* 2013)

LandscapeDNDC was validated using data obtained from Rothamsted Research's long-term agricultural experimental plots in Hertfordshire, England. Data for three winter wheat plots were used including a mineral-fertilised plot and two manure application plots (Table 2.4). This dataset was chosen as soil carbon measurements were available since 1975 as well as management practices and soil characteristic have been monitored since 1844 for which the model could be validated against. Fertiliser was applied once per year for plots 8, 21 and 22 and actual sowing, fertiliser application and harvest dates were used in the model validation process. For LandscapeDNDC to run more effectively for UK scenarios, crop parameters within the model were altered from default values to those more realistic for UK winter wheat. This included the partitioning of winter wheat roots, straw and grain parts are based on data from the Wheat Growth Guide (HGCA, 2008;

Sylvester-Bradley and Clarke, 2009) and model calibration. Grain weight is more than twice that of straw; and roots represent a small part of the whole plant. Values for winter wheat yields under optimal fertiliser application were also extracted from the same report. According to which the maximum total dry matter production for winter wheat in northern Britain is more than 20 t/ha. Grain and straw CN ratios were estimated using data from the wheat growth guide and the "Using grain N% as a signature for good N use" HGCA report. The values used for these parameters in LDNDC were based on two facts:

1. the N in straw is less than half of that in grain.
2. under optimal fertiliser-N input around 2% of the grain is N.

Following the modification of crop parameters, LandscapeDNDC fitted the measured data (Appendix 2.3; Figures A2.3.1 and A2.3.2). Results are shown for 1975-2010. LandscapeDNDC does not include a spin up period which models the effect of land use and management over a long period prior to the study period. However each plot was run for an additional 5 years (1970-1975) giving a five year 'initialisation' phase which was intended to allow the carbon pools in the model to reach and initial balance.

Table 2.4 Site characteristics for Rothamsted Research cropland plots

	Plot 8	Plot 21	Plot 22
Elevation (m)	128	128	128
Latitude	51.82	51.82	51.82
Longitude	0.35	0.35	0.35
SOC content (g/kg)	10.7	25.9	30.3
Humus	Mull	Mull	Mull
Soil Type	Clay Loam	Clay Loam	Clay Loam
Bulk density	1.2	1.08	1.08
Clay	25.2	25.2	25.2
Depth (mm)	230	230	230
Height of soil layer in soil strata (mm)	2.3	2.3	2.3
pH	7.35	7.35	7.35
Tillage depth (cm)	23	23	23
Fertiliser	Ammonium nitrate	Manure (FYM)	Manure (FYM)

Modelling scenarios to assess the impact of agricultural management upon soil carbon stocks were developed that represent realistic management options. These were centred on four main themes (Table 2.5):

1. Residue returns.
2. Tillage intensity.
3. Fertiliser application rate.
4. Manure applications.

As shown in Table 2.5, scenarios included increasing residue returns from 15% (baseline) to 30 and 50% residues remaining. LandscapeDNDC describes tillage intensity in terms of depth tilled as opposed to machinery used. As conventional tillage is assumed for the baseline (20cm), modelling scenarios focused on describing the reduction and exclusion of tillage, therefore applying a 10cm and 0cm tillage depth scenario. Three applications of ammonium nitrate (AN) fertiliser were applied as standard practice for winter wheat plots. To determine how the quantity of AN application influences soil carbon stocks, ±50% application quantities of AN were applied. The combination of AN and manure fertiliser application in comparison to AN-only are also investigated at standard rates and -50% application quantity. A scenario of +50% manure application was not run as this is unlikely to occur due to NVZ regulations.

LandscapeDNDC models were run to 23 cm to agree with the validation runs. Running the model to 100cm did not change shape of the curves for the different scenarios, but total SOC stocks were higher because of the additional carbon stocks between 23 and 100 cm.

Table 2.5 Description of Landscape DNDC modelling scenarios

	SCENARIO	Residue Return (%)	Tillage	Fert 1	Date	Quantity (kg/ha)	Fert 2	Date	Quantity (kg/ha)	Fert 3	Date	Quantity (kg/ha)	Fert 4	Date	Quantity (kg/ha)	Total N Application
10 g/kg C	**Baseline**	**15**	**20**	**AN**	**06-Apr**	**50**	**AN**	**26-Apr**	**80**	**AN**	**07-May**	**80**				**210**
	Residue	30	20	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Residue	50	20	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Till-zero	15	0	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Till-Reduced	15	10	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Fert +50%	15	20	AN	06-Apr	75	AN	26-Apr	120	AN	07-May	120				315
	Fert -50%	15	20	AN	06-Apr	25	AN	26-Apr	40	AN	07-May	40				105
	Manure	15	20	AN	06-Apr	33	AN	26-Apr	80	AN	07-May	80				193
	Manure	15	20	AN	06-Apr	33	AN	26-Apr	80	AN	07-May	80	FYM	30-Sep	170	363
	Manure - 50%	15	20	AN	06-Apr	41.5	AN	26-Apr	80	AN	07-May	80				
	Manure - 50%	15	20	AN	06-Apr	41.5	AN	26-Apr	80	AN	07-May	80	FYM	30-Sep	85	363
20 g/kg C	**Baseline**	**15**	**20**	**AN**	**06-Apr**	**50**	**AN**	**26-Apr**	**80**	**AN**	**07-May**	**80**				**210**
	Residue	30	20	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Residue	50	20	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Till-zero	15	0	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Till-Reduced	15	10	AN	06-Apr	50	AN	26-Apr	80	AN	07-May	80				210
	Fert +50%	15	20	AN	06-Apr	75	AN	26-Apr	120	AN	07-May	120				315
	Fert -50%	15	20	AN	06-Apr	25	AN	26-Apr	40	AN	07-May	40				105
	Manure	15	20	AN	06-Apr	33	AN	26-Apr	80	AN	07-May	80				193
	Manure	15	20	AN	06-Apr	33	AN	26-Apr	80	AN	07-May	80	FYM	30-Sep	170	363
	Manure - 50%	15	20	AN	06-Apr	41.5	AN	26-Apr	80	AN	07-May	80				
	Manure - 50%	15	20	AN	06-Apr	41.5	AN	26-Apr	80	AN	07-May	80	FYM	30-Sep	85	278

2.2.1 Landscape DNDC Results

Results obtained using LandscapeDNDC for the baseline scenario showed some variation in SOC stocks. In part this is due to variation in weather between years, but there is also a long term trend of decreasing SOC stocks, particularly for the 20 g/kg initial C. This is an artefact of the LandscapeDNDC model resulting for the lack of a detailed spin up period. The apparent decrease in SOC in the modelled results suggests that the five year period (1970 – 1975) used to initialise the model was not long enough for modelled SOC stocks to have reached equilibrium. Because of this the effect of the modelled management regimes should be assessed relative to the baseline scenario, rather than as absolute values.

Results for the LandscapeDNDC scenarios show that an increase in residue returns had a positive effect on soil carbon at both 10 and 20 g/kg initial C. (Figure 2.8). Doubling residue returns from 15% (baseline) to 30% resulted in an increase in average annual soil carbon stock (1975 to 2010) of 0.780 to 0.788 tC/ha for initial SOC contents of 10 g/kg and 20 g/kg respectively (Table 2.6). This increase in soil carbon stock doubled at 50% residue returns, with an increase of 1.559 to 1.594 tC/ha compared to the baseline and an increase of 0.779 to 0.806 tC/ha from the 30% residue scenario. Overall this relates to an increase in SOC stock of 1 to 3% of the baseline value when residue returns increase to 50%.

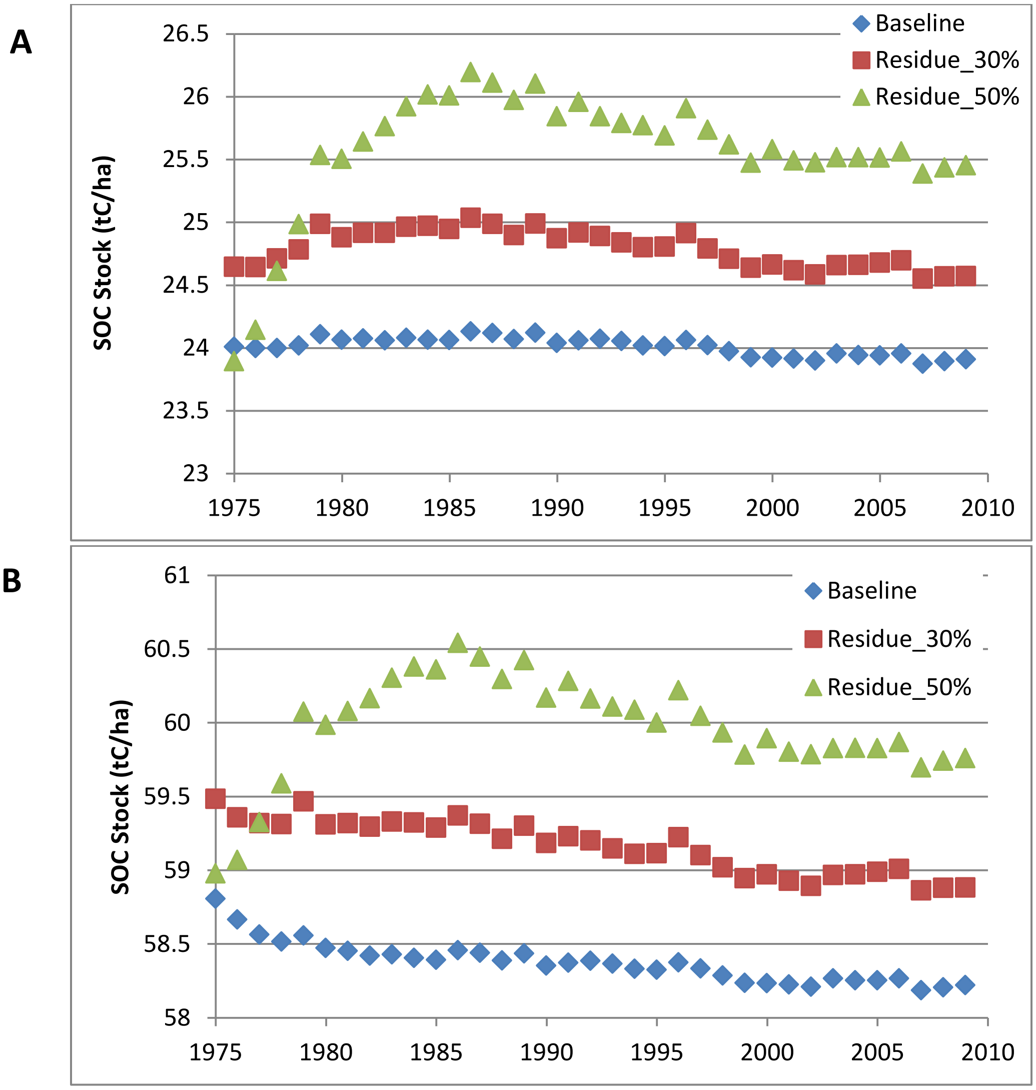

Figure 2.8 Modelled SOC stock for residue returns of Baseline (15%), 30% and 50% residue returns at 10 g/kg C (A) and 20 g/kg C (B) initial soil carbon content

The reduction of tillage to 0cm and 10cm compared to the baseline (20cm tillage depth) showed a positive effect on average annual soil carbon (1975 to 2010) for Rothamsted site characteristics (Figure 2.9). Average soil carbon stocks increased by 0.056 to 0.061 tC/ha when tillage depth decreased from 20cm (baseline) to 10cm depth. A larger increase in average soil carbon stock was seen at 0cm tillage depth, differing from the baseline by 0.234 to 0.245 tC/ha. However to put into perspective these changes in soil carbon were <1% of the baseline soil carbon stocks.

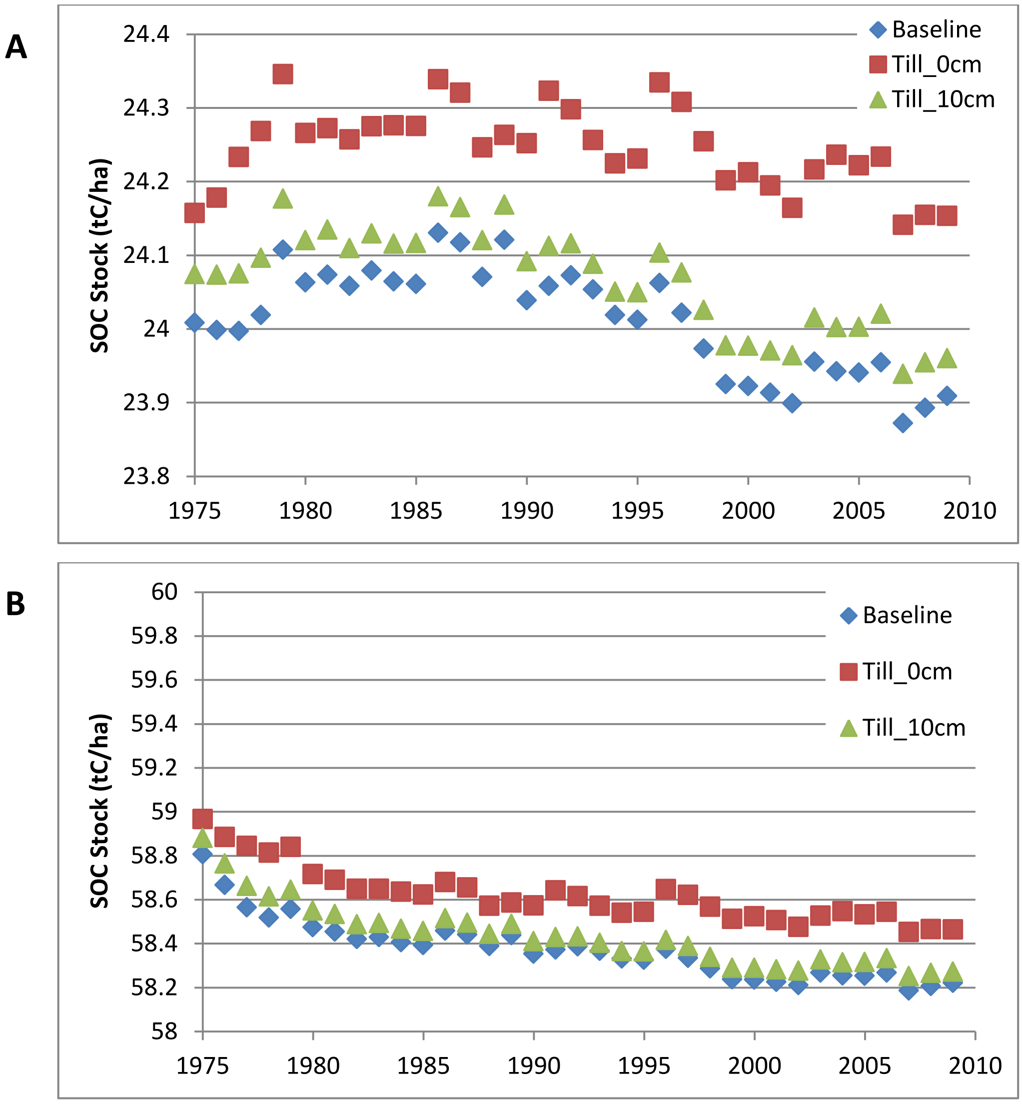

Figure 2.9 Modelled SOC stock for tillage regimes of Baseline (20cm), 0cm and 10cm tillage depth at 10 g/kg C (A) and 20 g/kg C (B) initial soil carbon content.

Baseline fertiliser applications of ammonium nitrate were 210 kg/ha/year with mitigation scenarios were assumed to be +50% (315 kg/ha/year) and -50% (105 kg/ha/year) ammonium nitrate. Results for +50% and -50% fertiliser applications showed positive and negative effects respectively on average modelled soil carbon (Figure 2.10). A 50% increase in ammonium nitrate application resulted in an increase in average soil carbon content of 0.428 tC/ha (for both 10 and 20 g/kg initial C). A 50% reduction in ammonium nitrate application resulted in a decrease in average soil carbon content of -0.261 to-0.272 tC/ha.

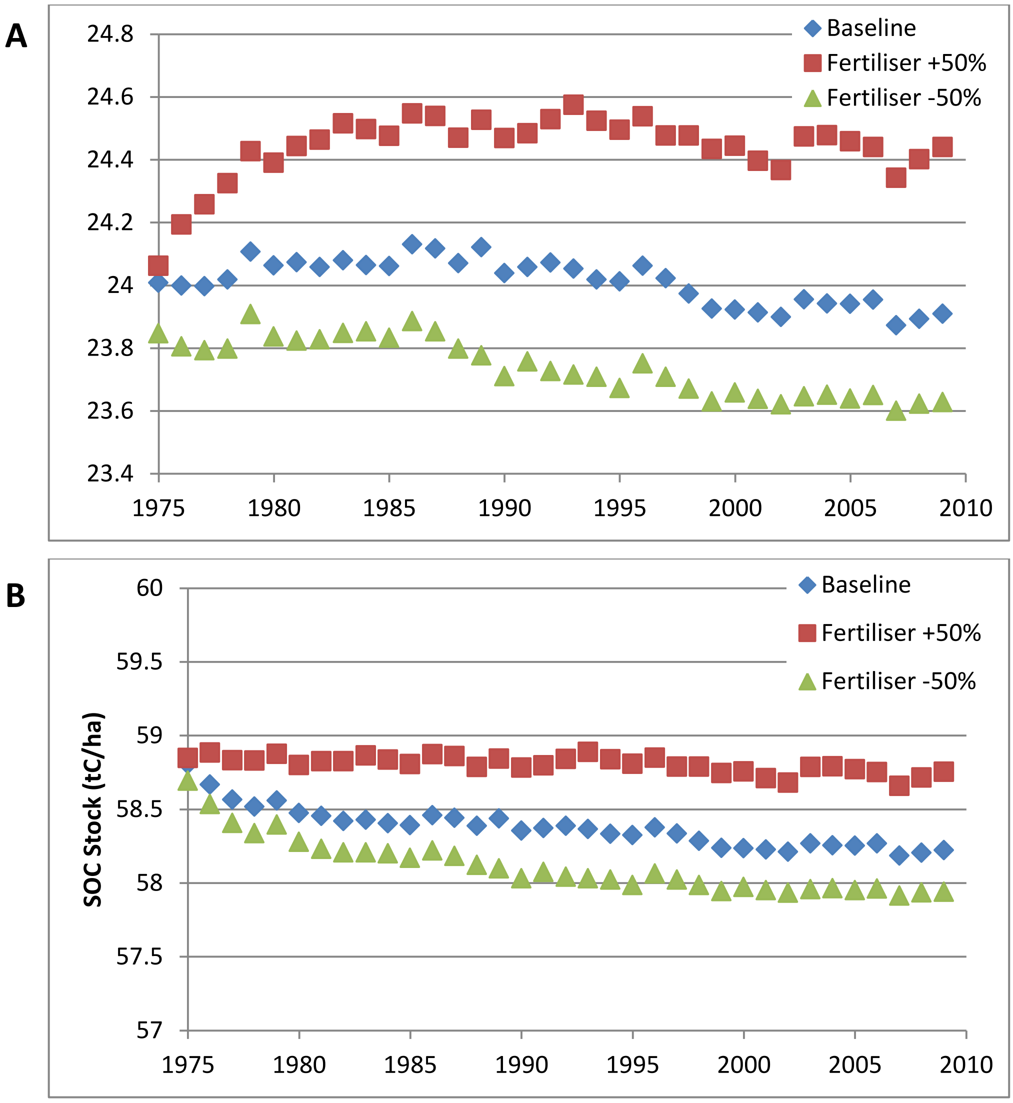

Figure 2.10. Modelled SOC stock for fertiliser applications of Baseline (210 kg N/ha), +50% additions (315 kg N/ha) and -50% fertiliser application (105 kg N/ha) at 10 g/kg C (A) and 20 g/kg C (B) initial soil carbon content

The application of manure fertiliser showed consistent increases in modelled mean soil carbon stocks (1975 to 2010) (Figures 2.11 and 2.12). When manure was not applied (193 kg N/ha/year, ammonium nitrate) mean soil carbon stocks were minimally less (-0.044 to -0.046 tC/ha) than the baseline (210 kg N/ha/year, AN). With the addition of manure (363 kg N/ha/year; 193 kg N/ha/year AN and 170 kg N/ha/year FYM) average modelled soil carbon stocks (1975-2010) increased by 3.902 to 3.923 tC/ha. When contributions of manure were halved to 85 kg N/ha/year (with 193 kg N/ha/year AN) the influence on soil carbon stocks with manure application was still positive with average modelled soil carbon stocks increased by 1.847 to 1.867 tC/ha from baseline soil carbon stocks but less marked compared to manure additions of 170 kg N/ha/year. (Figure 2.11 and 2.12, Table 2.5).

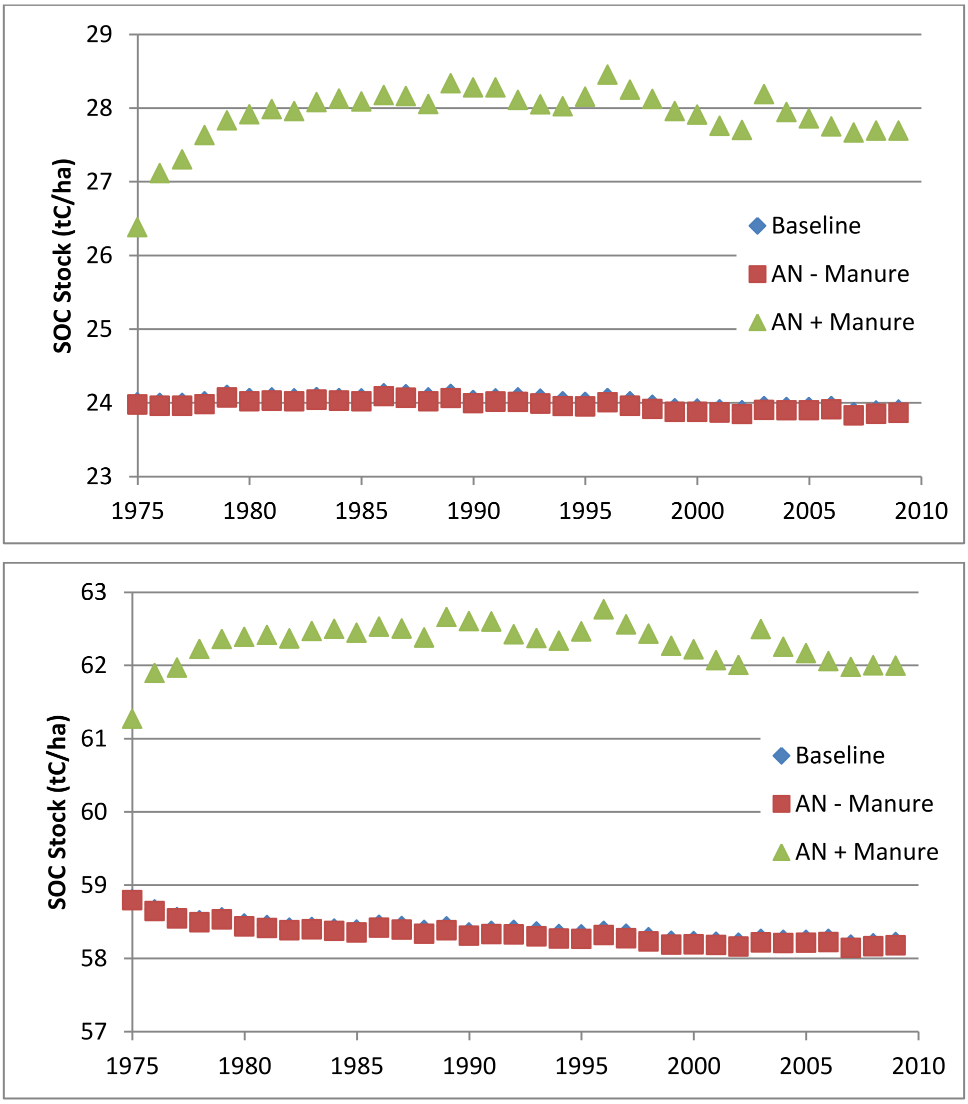

Figure 2.11 Modelled SOC stock for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (193 kg N/ha) and AN and manure application at 363 kg N/ha (193 kg AN/ha and 170 kg Manure/ha) at 10 g/kg C (A) and 20 g/kg C (B) initial soil carbon content (AN = ammonium nitrate)

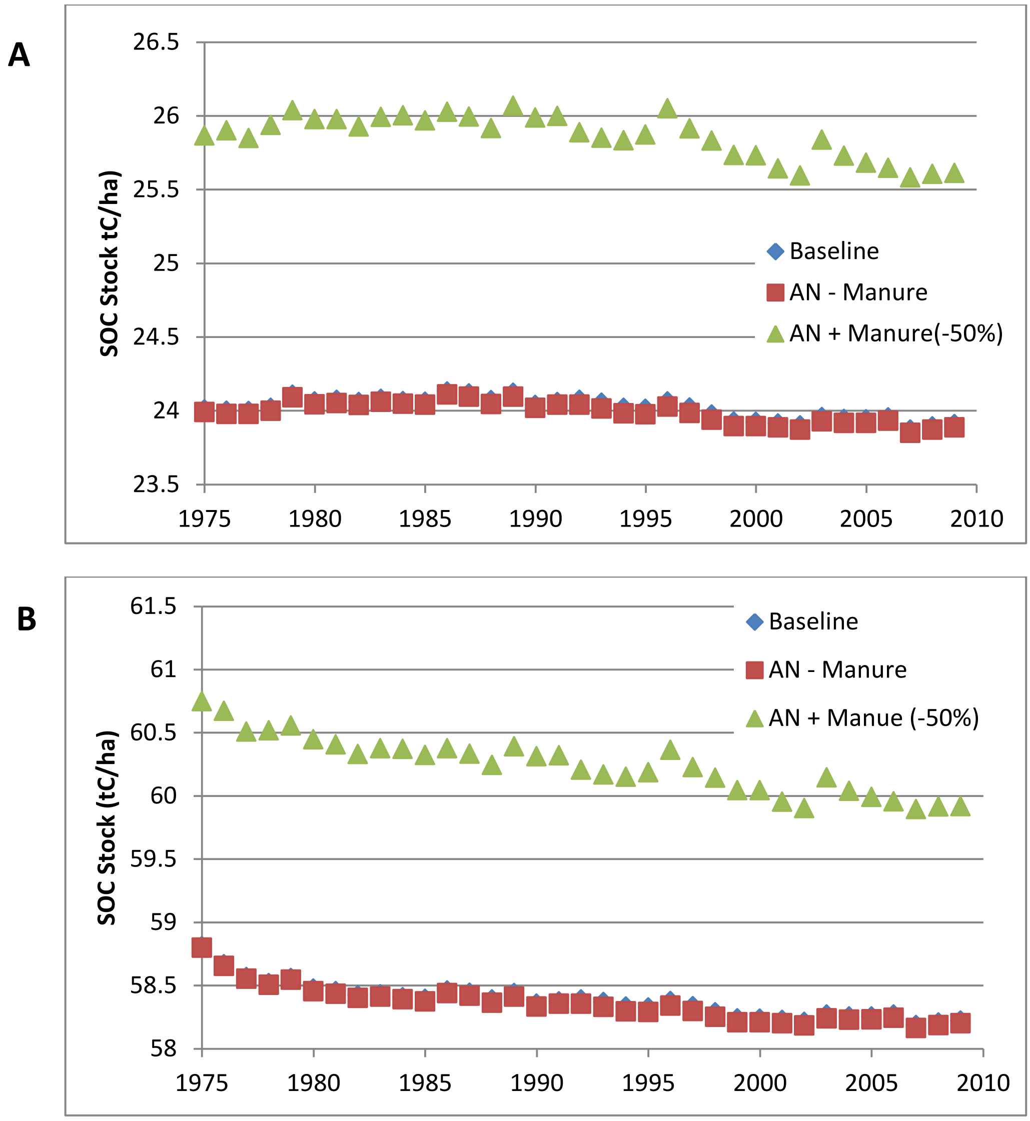

Figure 2.12 Modelled SOC stock for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (201 kg N/ha) and AN and manure application at 286 kg N/ha (201 kg AN/ha and 85 kg Manure/ha) at 10 g/kg C (A) and 20 g/kg C (B) initial soil carbon content (AN = ammonium nitrate).

The data shown in Figures 2.8 – 2.12 are tabulated in Appendix 2.4 Tables A2.4.1 and A2.4.2

The results from Landscape-DNDC modelling showed that increased residue returns, reduced tillage, increased mineral and manure fertilisers increased soil carbon stocks. However these management options also led to an increased in CO_2 and N_2O fluxes compared to the baseline management scenario (Tables 2.7 and 2.8). Greenhouse gas emissions were lower than the baseline when N or C inputs were less than in the baseline scenario (e.g. Fertiliser -50%). This highlights the importance of assessing management effects on soil carbon over a full budget scale to determine any significant trade-offs. However, results shown are based on one agricultural system that is assumed to UK-typical, results may vary with different soils and climatic conditions, and their interaction with the management practices adopted. In addition, the models are based on assumptions and hence current understanding. However, recent work on minimum tillage has illustrated that the effect of this management practice on soil carbon storage is a function of the depth to which the measurements have been taken, may affect SOC stocks below the 23 cm depth modelled by LDNDC. In addition, with regards to tillage events, soil biogeochemistry within the LandscapeDNDC model assumes that the organic matter is equally distributed in the plough layer, which may not be the case in practice.

Table 2.6 Landscape DNDC modelled mean annual soil carbon stocks by scenario (1975 to 2010) and difference to baseline management.

		Baseline	R30	R50	T0	T10	F+50	F-50	AN	AN+M	AN	AN+M-50%
10 g/kg initial C	Mean annual C stock tC/ha	24.01	24.79	25.80	24.24	24.07	24.49	23.74	23.97	27.91	23.99	25.86
	Difference in C stock tC/ha (Scenario - Baseline)		0.780	1.790	0.234	0.056	0.428	-0.272	-0.046	3.902	-0.025	1.847
20 g/kg initial C	Mean annual C stock tC/ha	58.37	59.16	60.16	58.622	58.440	58.80	58.11	58.33	62.30	58.35	60.24
	Difference in C stock tC/ha (Scenario - Baseline)		0.788	1.654	0.245	0.061	0.428	-0.261	-0.043	3.923	-0.024	1.867

Table 2.7 Landscape DNDC modelled mean annual soil CO_2 flux stocks by scenario (1975 to 2010) and difference to baseline management.

		Baseline	1	2	3	4	5	6	7	8	9	10
			R30	**R50**	**T0**	**T10**	**F+50**	**F-50**	**AN**	**AN+M**	**AN**	**AN+M-50%**
10 g/kg initial C	Mean annual CO_2 flux (kg/ha)	341.5	544.3	808.8	394.5	360.3	454.7	267.3	329.5	2448.2	335.3	1399.0
	Difference (Scenario - Baseline)		202.8	467.3	52.9	18.7	113.2	-74.2	-12.0	2106.6	-6.2	1057.4
20 g/kg initial C	Mean annual CO_2 flux (kg/ha)	357.5	562.3	829.1	412.4	377.2	470.0	286.1	346.2	2469.3	351.5	1419.8
	Difference (Scenario - Baseline)		204.8	471.6	55.0	19.7	112.5	-71.4	-11.3	2111.8	-5.9	1062.3

Table 2.8 Landscape DNDC modelled mean annual soil N_2O flux stocks by scenario (1975 to 2010) and difference to baseline management.

		Baseline	1 **R30**	2 **R50**	3 **T0**	4 **T10**	5 **F+50**	6 **F-50**	7 **AN**	8 **AN+M**	9 **AN**	10 **AN+M-50%**
10 g/kg initial C	Mean annual N_2O flux (kg/ha)	0.272	0.326	0.394	0.315	0.276	0.399	0.193	0.260	0.963	0.266	0.620
	Difference (Scenario - Baseline)		0.05	0.12	0.04	0.00	0.13	-0.08	-0.01	0.69	-0.01	0.35
20 g/kg initial C	Mean annual N_2O flux (kg/ha)	0.282	0.340	0.393	0.334	0.287	0.420	0.205	0.270	0.989	0.275	0.629
	Difference (Scenario - Baseline)		0.06	0.11	0.05	0.01	0.14	-0.08	-0.01	0.71	-0.01	0.35

2.3 Comparison of Landscape and DailyDayCent DNDC results

Table 2.9 compares the simulation results of the two models DNDC and DailyDayCent for the Rothamsted test site showing the SOC changes for changed management over a period of 35 years in t/ha/y. The assumptions for the mitigations option are the same in both models (see Table 2.1 and Appendix 2.1) except for low tillage. Here the modifications differ, because of the model structure. In Landscape DNDC the affected depth changed, while in DailyDayCent different parameters are used for the same depth. The scenarios 7-10 consider manure application (in scenario 8 and the half of this amount in scenario 10) additional to the fertiliser application (baselines scenarios 7 and 9).

Table 2.9 Stock change factors for average annual change in SOC during the study period with the different mitigation options for the Rothamsted site.

Treatment	DDC 20 years	DDC 35 years	LDNDC 35 years	IPCC default Stock Change factor 20 years
70% residue removal	1.010	1.007	1.0009	1.00[a]
50% residue removal	1.020	1.016	1.0019	1.11[b]
no tillage*	1.006	1.005	1.0003	1.15
low tillage*	1.007	1.005	1.0001	1.08
double fertiliser	1.007	1.005	1.0005	
half fertiliser	0.995	0.995	0.9997	
double manure	1.027	1.021		1.44[c]
half manure	1.014	1.011		

*in Landscape DNDC the affected depth changed, while in DailyDayCent different parameters are used for the same dept
a – default factor for medium residue input
b – default factor for high residue input
c - default factor for high residue input plus manure.

LandscapeDNDC and DailyDayCent are biogeochemical models. Previous versions were developed for different purposes and therefore they differ in structure and also in the consideration and determination of the different processes. One of the most crucial differences between the models for the study presented here is consideration of soil depth. While the simulation of the carbon dynamics in DailyDayCent is restricted to the top 20 cm of the soil, LandscapeDNDC considers the upper 23 cm of the soil.

The simulation runs show similar directions of change for both models but different magnitude of change. Changes modelled by DailyDayCent were more than those modelled by LandscapeDNDC. Both DailyDayCent and LandscapeDNDC showed that the highest mitigation was achieved by increasing manure application (scenario 8, Table 2.8). Both models showed that reduction of residue removal was also effective in increasing SOC. Finally, both models showed that tillage reduction and changes in fertiliser management were least effective in increasing SOC stocks. From the modelled results it is not clear whether the mitigation potential depends of the initial SOC values or not.

For similar mitigation actions presented in the literature review, the addition of mineral N and manure fertilisers to intensively managed pasture was shown to increase in soil C. The effect of reduced/no tillage showed inconsistent results with respect to its influence on soil C. Modelling showed reduced/no tillage to have a positive effect, however this only considered changes SOC stock in the top 20 cm (DDC) or 23 cm (LDNDC) rather than the full soil depth. This may over estimate SOC increases as the literature review showed that increases in SOC stock in the upper soil may be counteracted by reduction of SOC stock in deeper layers. Moreover, the modelling work only considered a limited number of sites and therefore may not fully reflect geographical variation across the UK. Other influences on SOC stocks discussed in the literature review were not included in the modelling work.

3 Use of IACS data to quantify regional crop rotation patterns for use in the LULUCF Sector of the Greenhouse Gas Inventory

Crop rotation patterns are an important part of UK farm management practices. Hard information on regional patterns, rotation lengths and the use of grass leys is impossible to obtain directly from data sources. Current knowledge of regional crop rotation patterns in the UK Greenhouse Gas (GHG) Inventory in general and in the LULUCF Sector (Land Use, Land Use Change and Forestry), in particular, is based on survey data and expert judgment.

Crop-grass rotations may also be conflated with more permanent land use change, leading to inaccurate estimates of the impacts of land use change on soil carbon. To be able to quantify spatial-temporal patterns of rotations for the UK as a whole and for the regions, field level data are required to track changes over time. The patterns identified can then be aggregated to the required resolution as part of the activity data compilation.

To allow identification of regionally-specific rotation patterns, such as soil carbon stock changes and nitrous oxide (N_2O) emissions arising from land use change, access to existing detailed spatial data on field level crops is required. These data exist in the IACS/RPA systems for all fields for which subsidies are paid (approx. 2005 to 2012, country dependent) and coverage of the database has been improving since the spatial databases were introduced (as elucidated in the PIACS project (Smith *et al*. 2010)).

3.1 Methodology

The licensing and acquisition of the field level IACS/RPA datasets from the Devolved Administrations (DAs) of the United Kingdom has been a very length process, partly because the complete datasets are very rarely used for research in such detail (see Section 3.1.2 for details on the current status). The four separate DA datasets, require separate processing workflows due to differences in the data structures, formats and level of detail between the DAs, but using the same overarching methodology. The differences between the DAs were due to differences in the formats in which data were provided (various ArcGIS formats, databases and plain text files) and the data structure (notation used, categorization methods, treatment of duplicate records etc.).

The data were pre-processed to ensure all field level records used a homogenous structure; the raw data came in various forms – sometimes differing between years within a single DA – so was put through a series of steps to remove extraneous, duplicate and unusable records. Another part of this process was to convert the wide-ranging crop type and field-use assignations to aggregated categories for assimilation into the LULUCF inventory. The aggregated codes used here are Crop Annual (CA), Crop Perennial (CP), Grass Not Known (GNK; includes grass under schemes such as Countryside Stewardship and also clovers, where no information was available on the age of the sward), Grass Permanent (GP; grass 5 years and older), Grass Temporary (GT; grass under 5 years old), Forest (F), Forest – previously Pasture (FPP, IACS code FR4; forested land that was pasture until a certain date, e.g. until May 2003 in the datasets for England) and Other (O). Any area where no IACS/RPA data exist (i.e. non-agricultural land, fields not subsidized or with no subsidy claimed) was classified as ‘No Data’.

Following this processing, field level records for each given year were converted to a 25 m grid resolution where each grid cell contains only a single Land Category. The chosen spatial resolution balances the level of detail retained against processing time, ensuring that over 99.98% of individual fields were represented, i.e. all but the very smallest land parcels. Using a grid based approach rather than vector-based change analysis enabled a consistent comparison of land use change between years. Unique codes for each of the nine Land Categories (including 'No Data') were created and then compared between years for every grid cell. This resulted in one of 81 possible land use change combinations across two years being assigned to every grid cell.

3.1.2 Datasets

3.1.2.1 England

Data provision: 2005 to 2013 in one large spatial database containing >6.2 million records in polygon form.
Data characteristics: The data do not allow for detailed crop rotation analysis, due to all major crop categories (cereals, root crops, fruit etc.) being aggregated into a single IACS category (FV1). However, this does not affect the usefulness of the dataset for the purpose of estimating land use change for the LULUCF inventory. There is good concordance in data structure across all years, with spatial details increasing in later years.

3.1.2.2 Wales

Data provision: 2004 to 2012 in two distinct datasets; 2004 to 2006 (field polygons plus annual point data files representing subsidy claims) and 2007 to 2012 (field polygons plus annual crop subsidy claim data tables linked to field polygons via unique IDs).
Data characteristics: The earlier field records needed to be joined to the claim points based on their spatial location, while the later field records were joined via unique IDs. There were significant issues in understanding data structure, composition, duplicated records and the change of collection methods in 2011, however these have been resolved.

3.1.2.3 Scotland

Data provision: The data licensing agreement was signed in April 2014 after lengthy negotiations, but actual data have not arrived at the time of writing.

3.1.2.4 Northern Ireland

Data provision: Field polygons were provided for 2005, 2011 and 2012, but no crop and claim information has been provided at the time of writing.

3.2 Results

The detailed methodology was developed using pilot areas of 25 km by 25 km area in both England (north Oxfordshire) and Wales (Powys) to establish appropriate methods for processing the data into a usable form and performing land use change analysis. Two concurrent years were chosen for each test area that did not cross periods of change in data collection methods (Section 3.1.2); 2005 and 2006 were studied in England and 2008 and 2009 in Wales.

3.2.1 Wales

Pre-processing of the data for validation purposes was encouraging with 90% of spatially distinct field records retained on average. The two main issues involved missing crop information and duplicated crop records per field ID. Conversion from field polygons to 21,184 gridded polygons resulted in little loss of field shape and area representation due to the high resolution of the grid (25 m by 25 m).

A series of change matrices were created to analyse the annual land use change for 2007 to 2008 and 2008 to 2009. Any cell classified as 'No Data' – in either or both years – was discarded as change could not be observed. This resulted in a land use change analysis for 13,232 km^2 for 2007/8 and 13,285 km^2 in 2008/9 (approx. 61% of the country). Figures 3.1 (2007/8) and 3.2 (2008/9) show the breakdown of the land use change from one year to the next.

% Land Use change not including any gridcells that have No Data (in either or both years)

07 \ 08	No Data	CA	CP	F	FPP	GNK	GP	GT	O	Total
No Data	-	-	-	-	-	-	-	-	-	-
CA	-	3.76%	0.00%	0.00%	-	0.01%	0.26%	0.54%	0.01%	4.58%
CP	-	0.00%	0.02%	-	-	0.00%	0.00%	0.00%	0.00%	0.03%
F	-	0.00%	0.00%	2.44%	-	0.00%	0.04%	0.00%	0.05%	2.54%
FPP	-	-	-	-	-	-	-	-	-	0.00%
GNK	-	0.01%	-	0.00%	-	0.05%	0.00%	0.01%	0.00%	0.08%
GP	-	0.90%	0.00%	0.11%	-	0.00%	85.84%	0.08%	0.10%	87.05%
GT	-	0.50%	0.00%	0.00%	-	0.01%	0.69%	2.93%	0.00%	4.13%
O	-	0.02%	0.00%	0.04%	-	0.00%	0.07%	0.01%	1.44%	1.59%
Total	-	5.21%	0.03%	2.61%	0.00%	0.08%	86.90%	3.57%	1.60%	100.00%

Figure 3.1. Land use change matrix for Wales (2007 to 2008) CA = Crop Annual, CP = Crop Perennial, F = Forest, FPP = Forest - previously Pasture, GNK = Grass Not Known, GP = Grass Permanent, GT = Grass Temporary and O = Other.

% Land Use change not including any gridcells that have No Data (in either or both years)

08 \ 09	No Data	CA	CP	F	FPP	GNK	GP	GT	O	Total
No Data	-	-	-	-	-	-	-	-	-	-
CA	-	4.31%	0.00%	0.00%	-	0.02%	0.33%	0.58%	0.00%	5.25%
CP	-	0.00%	0.03%	0.00%	-	-	0.00%	0.00%	0.00%	0.03%
F	-	0.00%	0.00%	2.80%	-	0.00%	0.03%	0.00%	0.01%	2.84%
FPP	-	-	-	-	-	-	-	-	-	0.00%
GNK	-	0.01%	-	0.00%	-	0.07%	0.00%	0.00%	0.00%	0.09%
GP	-	0.68%	0.00%	0.08%	-	0.00%	85.74%	0.08%	0.04%	86.63%
GT	-	0.29%	-	0.00%	-	0.00%	0.65%	2.65%	0.00%	3.59%
O	-	0.01%	0.00%	0.02%	-	0.00%	0.04%	0.01%	1.50%	1.57%
Total	-	5.30%	0.03%	2.91%	0.00%	0.10%	86.79%	3.31%	1.56%	100.00%

Figure 3.2 Land use change matrix for Wales (2008 to 2009) CA = Crop Annual, CP = Crop Perennial, F = Forest, FPP = Forest - previously Pasture, GNK = Grass Not Known, GP = Grass Permanent, GT = Grass Temporary and O = Other.

In summary, 96.5% of the area with known Land Categories in 2007/8 underwent no change, rising to 97.1% in 2008/9; both change analyses were dominated by permanent grasses (GP) staying as permanent grasses. In the remainder of the area with known land use ('actual change'), permanent grass (GP) changing to annual crops (CA) was the primary change at 0.9% (2007/8) and 0.68% (2008/9). Exploring the 2008/9 results in more detail, Figures 3.3 to 3.6 show the spatial distribution of actual change and the bi-directional relationship of arable land and grasses.

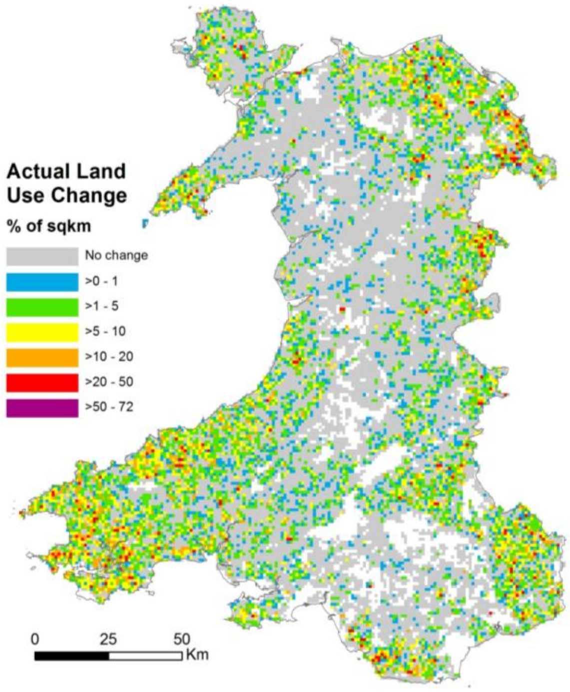

Figure 3.3 Actual land use change as proportion of a 1 km square

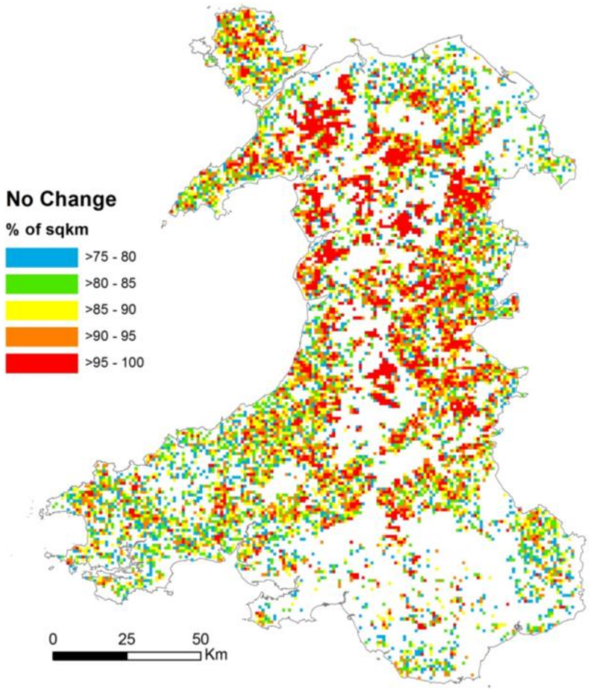

Figure 3.4 Areas of no change that constitutes >75% of a 1 km square

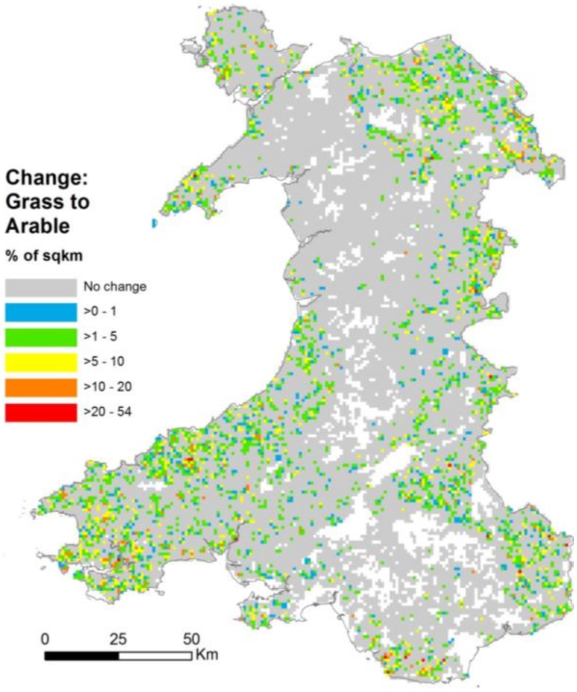

Figure 3.5 Grassland changing to arable land

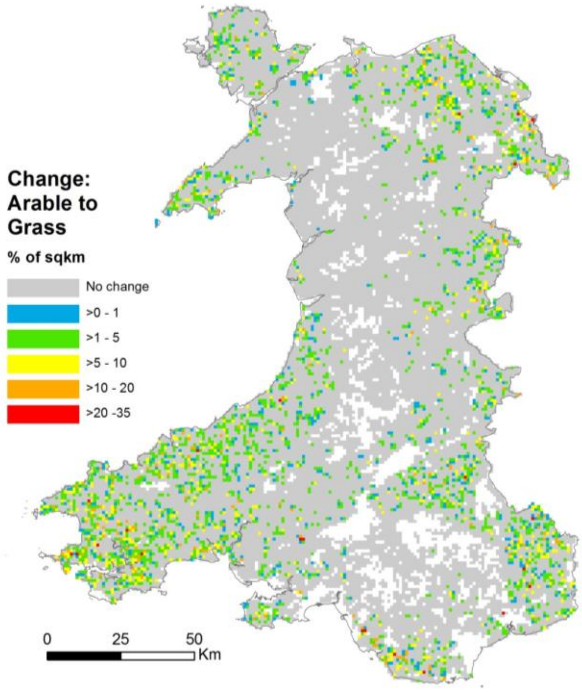

Figure 3.6 Arable land changing to grassland

Figure 3.3 shows that areas where actual change took place were predominantly in the lowland agricultural regions of the northeast, southeast and southwest – in the vast majority of cases, actual change was below 10% for a given 1 x 1 km square – while figures 3.5 and 3.6 show the distribution of the change relationship between arable land (annual and perennial crops combined) and grass land (permanent and temporary grasses combined).

For Figures 3.3, 3.5 and 3.6, grey represents the areas that underwent no land use change at all, while the areas represented by white indicate no data values with 90% to 100% coverage (the latter occurring with more regularity within the Brecon Beacons National Park, upland areas bordering the Snowdonia National Park and the Cardiff and Newport urban area). Figure 3.4 explores the areas of no change a little further and only highlights the areas in which no change was from 75% to 100% of a given km^2; the highest values falling upon upland areas that are claimed for under the Single Payment Scheme (SPS).

3.2.2 England

Pre-processing has been completed for all years for the entirety of England but grid creation and land use change analysis is undergoing processing at the time of writing.

For the test data area, over 99% of spatially distinct field records were retained. Within the 625 km^2 test area, around 75% of land was defined by a Land Category, while the remaining 'No Data' areas included any other land that was not included in the IACS system. This resulted in a land use change analysis for 469 km2, the results of which are shown in the land use change matrix in figure 3.7.

% Land Use change not including any gridcells that have No Data (in either or both years)

05 \ 06	No Data	CA	CP	F	FPP	GNK	GP	GT	O	Total
No Data	-	-	-	-	-	-	-	-	-	-
CA	-	50.38%	0.01%	0.09%	-	2.38%	0.57%	5.25%	-	58.68%
CP	-	0.04%	0.01%	-	-	-	0.02%	0.02%	-	0.08%
F	-	-	-	0.81%	-	-	0.01%	0.00%	-	0.82%
FPP	-	-	-	-	-	-	-	-	-	0.00%
GNK	-	-	-	-	-	-	-	0.01%	-	0.01%
GP	-	0.66%	0.02%	0.01%	-	-	27.47%	0.18%	-	28.35%
GT	-	5.24%	0.03%	0.06%	-	0.17%	0.45%	6.12%	-	12.06%
O	-	-	-	-	-	-	-	-	-	0.00%
Total	-	56.32%	0.07%	0.97%	0.00%	2.56%	28.51%	11.58%	0.00%	100.00%

Figure 3.7. Land use change matrix for a 25 km by 25 km pilot area in England (2005 to 2006) CA = Crop Annual, CP = Crop Perennial, F = Forest, FPP = Forest - previously Pasture, GNK = Grass Not Known, GP = Grass Permanent, GT = Grass Temporary and O = Other.

In summary, no land use change occurred in 85% of the known land use for the England pilot area. Approximately half of this area with no change was annual crops (CA), which may be expected in an arable region of the country. A relationship of temporary grass (GT) changing to annual crops (CA) and vice-versa accounted for a majority of the 15.2% of the area with known land use that did change.

3.3 Further work

Due to the very slow process of acquiring access to the IACS/RPA datasets from the DAs, this part of the project has been severely delayed. Upscaling the methodology from the pilot areas to the DA level is complete and national level results have been created or are in the process of being created, for operational use in the LULUCF. The national results could feed directly into the inventory methodology at an aggregated non-disclosive resolution, e.g. at a 1 km^2 grid. Methodologies have been developed to calculate the number of years that a given grid cell has existed in the designated Land Category, allowing the rate of change in carbon stocks to be estimated, and will be applied to the data once the land use change analyses are complete.

Data for Scotland and Northern Ireland have not been received at the time of writing but communications are ongoing. However, due to the extensive effort needed for both the acquisition and pre-processing of the data, in excess of the resources budgeted, it is proposed that these DAs are processed under future work, if the methodology is approved for inclusion in the inventory.

Making annual updates to the data in future during the inventory compilation process would be relatively straightforward as the more complex and time consuming stages have been completed and further data inputs would require considerably less effort (plus the required processing time). Annual analysis would also retain a steady flow of data, increasing efficiency of the methodology.

3.4 Conclusions

The methods developed here for land use change analysis are shown to work well at a national level (despite major efforts in data cleaning required at the pre-processing stage). It is expected that the work carried out under this project can be used directly to improve the LULUCF methodology, both in terms of spatial resolution and, most importantly, in the provision of reliable detailed data on annual agricultural land-use change that has not previously been possible. This would require regular annual data requests and data processing using the established methodologies for future years.

4 Reporting Emissions in the LULUCF Inventory

This section of the project examined the feasibility of reporting on the effect of land management activities on SOC stocks under Cropland and Grassland/Grazing Land in the UK using the methodology laid out in the IPCC 2006 Guidelines and assessed the potential of Grassland and Cropland management to increase SOC stocks using equation 1.1.

Decision trees for assessing SOC stock changes in Cropland and Grassland were developed for this project based on those in the IPCC 2006 AFOLU Guidance, but adapted for the UK. These are shown in Appendices 3.1 and 3.2. The IPCC Cropland decision tree includes 'other C increasing practices' which could include cover crops and grass in rotation. These have not been included in the UK decision tree. In the case of cover crops this was because of lack of evidence of their effect and limited activity data. For grass in rotation better information on rotation patterns was needed (see Section 3). Tillage has been included in the Cropland decision tree, although both the literature review and modelling suggests that it has no significant effect under UK conditions. This is to show how the effect of tillage could be incorporated in the LULUCF inventory if new evidence emerged.

For organic soils the main management action causing SOC stock change is drainage. The effect of drainage on histosols used as Cropland in England is already incorporated in the inventory using a Tier 1 approach. Recent work (Anthony et al, 2013) has updated estimates of areas of organic soils drained for agriculture which will allow improved reporting with full UK coverage including drained grassland. The IPCC Wetlands Supplement (IPCC, 2013) gives additional guidance on reporting emissions and SOC stock changes resulting from anthropogenic activity. Consideration of the implementing the Wetland Supplement guidance is beyond the scope of this report which focuses on the effect of management on mineral and organo-mineral soils.

4.1 Data requirements

The inputs needed to the quantifying change in SOC stocks are:

1) Reference values for soil carbon stocks under "native" (unmanaged) vegetation.
2) Time dependency of the change.
3) Activity Data.
4) Stock change factors

When these data are available annual change in SOC stocks can be obtained using equation 2.25 of the 2006 IPCC Guidance as described in Section 1.5 of this report. The first step towards being able to report changes in SOC stocks from Grassland and Cropland Management was to assess the availability of suitable data.

4.1.1 Reference SOC stocks

The SOC stocks for different land use classes in the UK which are used in the LULUCF inventory are taken from work by Bradley et al (2003, 2005) which derived the average SOC stocks to 1m under Cropland and Grassland for each UK administration. These average stocks which include mineral and organic soils are shown in Table 4.1. These values are assumed to be equilibrium SOC stocks.

Arable land in the UK is not under native vegetation, but has SOC stocks which are the result of management such as cultivation, drainage and grazing. There is little unmanaged arable land under "native" vegetation to assess what the SOC stocks of uncultivated arable land might be. The SOC stocks under arable land reported by Bradley et al (2003, 2005) there already includes the effect of cultivation. The SOC stocks for arable land under native vegetation were therefore estimated by dividing the SOC stock for cultivated arable land by the IPCC default stock change factor for cultivation (0.69)

Table 4.1 Soil Carbon stock to 1 m (t C/ha) for UK administrations

	Arable	Native (uncultivated) arable land	Grassland (pasture)	Grassland (semi-natural)
England	120	174	130	290
Scotland	150	218	230	330
Wales	110	159	140	230
Northern Ireland	150	218	210	390

4.1.2 Time dependence of SOC stock change

The IPCC default value for the time dependence of stock change factors is 20 years. The IPCC guidance assumes that changes in land management leads to a constant rate of change in SOC for a period of years following a land management change and the change stops at the end of the dependence period.

For Land Use Change the UK uses longer time dependencies. The mean time for changes causing carbon loss to reach equilibrium is 100 years throughout the UK. For changes which increase SOC stocks, the mean time to equilibrium is 200 years in England and Wales and 525 years for Scotland. An exponential trajectory of change is used with the greatest change occurring in the first few years following the change in management (Webb et al, 2013). The DailyDayCent modelling work (Section 2.1) supports the view that UK soils take more than 20 years to reach new equilibrium SOC stocks after a change in land management, with change continuing for at least 35 years for some treatments. Therefore the time dependencies used for land use change were used when assessing the effects of land management.

For SOC stock change resulting from land use change exponential trajectories of change are used. These reflect the fact that change is to be greatest in the years shortly after the change in use and then tail off over time. It might be expected that change in SOC stock resulting from change in Cropland and Grassland management would follow on similar trajectories. However, measured and modelled data on the trajectories of SOC stock change resulting from land management change are very limited, and so for this project the IPCC default trajectory of linear change was used. This approach could be modified in future as more date becomes available.

4.1.3 Activity Data

Sources of activity data for Grassland and Cropland management are shown in Table 4.2

Not all data sources cover all UK administrations for all years. The data sources available for each activity in each administration are shown in Table 4.2 which also contains details of strategies used to fill data gaps.

Table 4.2 Sources of activity data used to assess changes in SOC stocks due to Grassland and Cropland Management.

Activity	Data Source	Time scale	Geographic coverage	Comments
Crop and grass type	June Agricultural census data	1900 - date	UK. Separate surveys for each administration.	Some variation between administrations on terminology, but all collect data on areas of main agricultural activities collected. Data is a complete, long term, annual dataset which is updated annually using information submitted as part of the Single Farm Payment (SFP) scheme.
Residue removal rates	British Survey of Fertiliser Practice (BSFP) and expert judgement	1983 – date (gap 2004 – 2011)	E&W 1985 – 1995. GB 2004 – 2011	Data underlying Figure B2.6 of BSFP was used for winter wheat, winter barley and spring barley supplied by Defra. Removals for 1996 – 2004 estimated using 2004 – 2011 average. Residue returns from oats, oil seed rape, maize, sugar beet and other cereals estimated by ADAS.
Crop residue class	ADAS data on yield, dry matter and carbon returned.	2012.	UK	See Appendix 3.3. Residue returns for a given crop type are not judged to change greatly over time, so the 2012 data was used for all years.
Fertiliser and manure use	British Survey of Fertiliser Practice. A survey of Slurry Spreading Practices in Northern Ireland, Aubry et al (2012).	1942 – date (E&W) 1983 – date (Scotland)	GB	BSFP has a long term time series but does not cover NI. Data on practices in NI was taken from the Slurry Spreading Practices Survey, GB data and expert judgement by AFBI.
Tillage regimes	Farm Practice Survey (FPS) 2010 Survey of Scottish Agricultural Productions Methods (SSAPM) 2010. Scottish Survey of Farm Production and Methods (SSFPM) 2012	2010, 2012	FPS E&W only. SSAPM and SSFPM Scotland only.	No data for NI, but expert opinion from AFBI is that all tillage land in NI uses conventional tillage.
Grassland degradation	No suitable data set			There are no long-term UK-wide on erosion or other soil degradation, although some data on e.g peatland erosion and work is proposed to fill this gap.
Rotation pattern	Integrated Administration and Control System (IACS) data on land parcel use.	2004 - date	UK. Separate data collection for each administration	Rotation pattern has not been considered in this section of the report, but could be included when it is understood (see Section 3). IACS data is collected as part of the SFP scheme and is available UK wide although there are differences in classification systems. Protracted negotiation has been required to access IACS data.

Where gaps exist in data series these were filled by interpolation/extrapolation. Datasets tend to be more complete in more recent years. More gap filling was required in less recent years.

Similarly where data does not exist for a geographical area (e.g. lack of BSFP data for Northern Ireland), the data gap can be filled by transposing data from other areas ground-truthed against the more limited data information which is available (e.g. Aubry et al., 2012).

There are no complete data sets for the area of degraded (eroded) grassland in the UK. The IPCC default stock change factor of 0.95 for moderately degraded Grassland in temperate regions suggests areas were soil has lost 5% of its carbon content. It is unlikely that such carbon losses could occur on improved grassland, even if it was suffering from compaction or limited erosion in areas such as field gates or livestock feeders, and indeed the IPCC 2006 Guidance does not consider that improved Grassland can also be degraded. However, this scale of erosion could occur on areas of upland Grassland, particularly peatlands. Several reports have examined the extent of peat erosion in different parts of the UK (Natural England, 2012; Lilly et al, 2009 and Cummins et al, 2011), but at present there is no consistent dataset of the extent of soil erosion in the UK.

The approach taken assumes that management practices are independent of each other i.e crop type is assumed to be independent of tillage regime. This may not be the case in practice. This could lead to more complex interactions e.g. while tillage regime may not influence N requirements directly there could be an indirect influence if changes in crop type change N requirements. Similarly tillage reduction could increase compaction and so increase N_2O emissions. However, no data exists to enable interactions to be investigated e.g. to assess the proportion of reduced tillage land receiving high inputs.

4.1.4 Stock Change Factors

The IPCC AFOLU Guidelines (IPCC, 2006) give default SOC stock change factors for land management practices. These can be used for Tier 1 reporting in the absence of more specific national or regional factors. The default stock change factors applicable to the UK (temperate wet climate) are shown in Table 1.1 for Cropland and Table 1.2 for Grassland.

The modelling work carried out in Section 3 will allow UK specific stock change factors to be used for Cropland management activities. Table 2.3 compares stock change factors modelling using the DailyDayCent model with the IPCC default values.

As modelled stock change factors for Cropland management were not available in time to be used in this analysis, the default values for F_{LU}, F_{MG}, and F_i given in the IPCC 2006 AFOLU guidance were used for land used to assess change in Cropland SOC stocks. Given that the modelled stock change values in Table 2.3 are less than the IPCC defaults for all activities this is likely to over-estimate the upper limit of change possible.

Because of the lack of field data to calibrate and validate models, stock change factors were not modelled for Grassland management activities. The project team judged that the stock change factors given in the 2006 IPPC Guidance may not be appropriate for all UK Grasslands. In particular there were concerns that the stock change factor for improved Grassland might imply that measures such as drainage, liming, or fertiliser additions could increase SOC stock on high carbon organo-mineral soils. This is unlikely to be the case and extending these practices to organic and organo-mineral soils could lead to loss of SOC. Similarly use of the IPCC default factors might not accurately reflect the actual change in SOC stocks resulting from allowing marginal pasture to revert to rough grazing.

Further field investigation is needed to understand the effect of Grassland improvement practices on these soils, and also to understand the effect of allowing marginal improved pasture to revert to rough grazing.

The percentages of land receiving manure and fertiliser inputs were obtained from the British Survey of Fertiliser Practice. No similar data were available for Northern Ireland, so average values for Great Britain were used.

The percentage of land cultivated using reduced or no tillage techniques was obtained using the data sources shown in Table 4.2. It should be noted that the tillage regime is reported for a given year, and may not mean that land is cultivated in that manner in the long term. These data are therefore likely to over-estimate the proportion of land which is permanently under reduced or zero tillage regimes. Typical reduced tillage regimes in the UK include conventional ploughing approximately every three years to control weeds and reduce compaction. If reduced or zero tillage is only adopted for short periods the increases in SOC implied by the IPCC stock change factors are unlikely to be realised.

4.2 SOC Stock Change Estimates

Estimates of carbon stocks for each UK administration were made using the data sources described above. The estimates for each administration were then aggregated to give UK total changes.

4.2.1 SOC Stock changes from Cropland Management

SOC stocks for the UK can be derived using the Equation 1.1

The IPCC default stock change factors were used to estimate SOC stocks, as modelled factors were not available in time to be used. The stock change factors modelled using DailyDayCent having high uncertainty because of the very limited data available to calibrate the model, but suggest that the IPCC default factors may over-estimate the effects of Cropland management practices on SOC stocks in the UK. These estimates suggest that SOC stock of soils under Cropland in the UK fell by approximately 44 Mt between 1990 and 2012 (Figure 4.1), which would equate to a CO_2 emission of 161 Mt if all of this carbon was lost. However the main driver for this change in SOC stock was change in the Cropland area and exchange of land between different managements within the Cropland category, particularly between tillage land and set aside and fallow. In these cases the bulk of the carbon will remain in soil, but be transferred between land uses and management regimes.

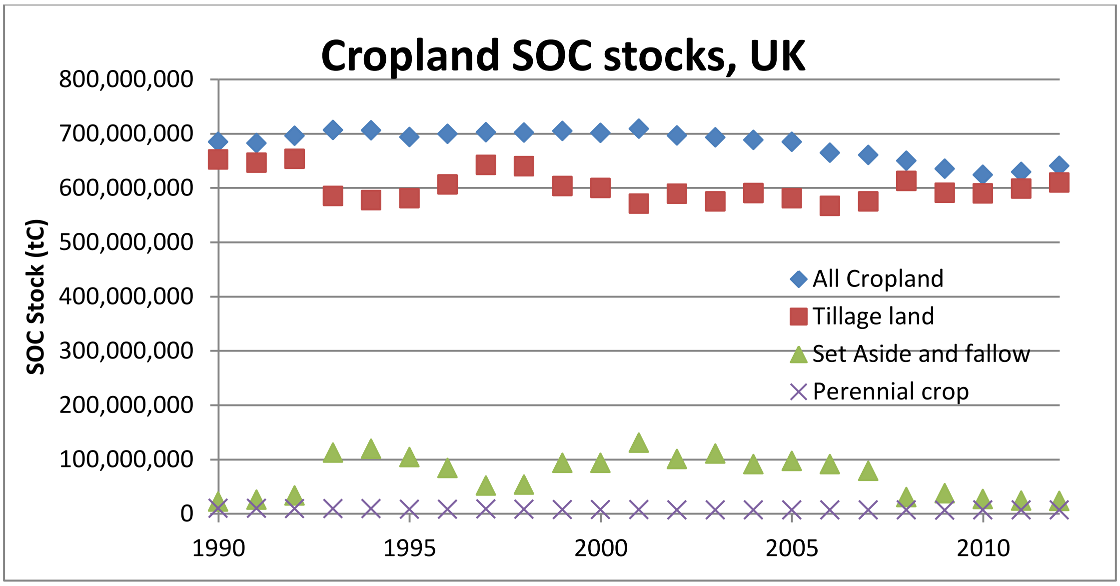

Figure 4.1 UK Cropland SOC stocks estimated using IPCC default stock change factors

Figure 4.2 shows the change in SOC stocks per hectare for Cropland, which gives a more accurate representation of change due to change in management practices, and shows that stocks per hectare do not vary greatly over time.

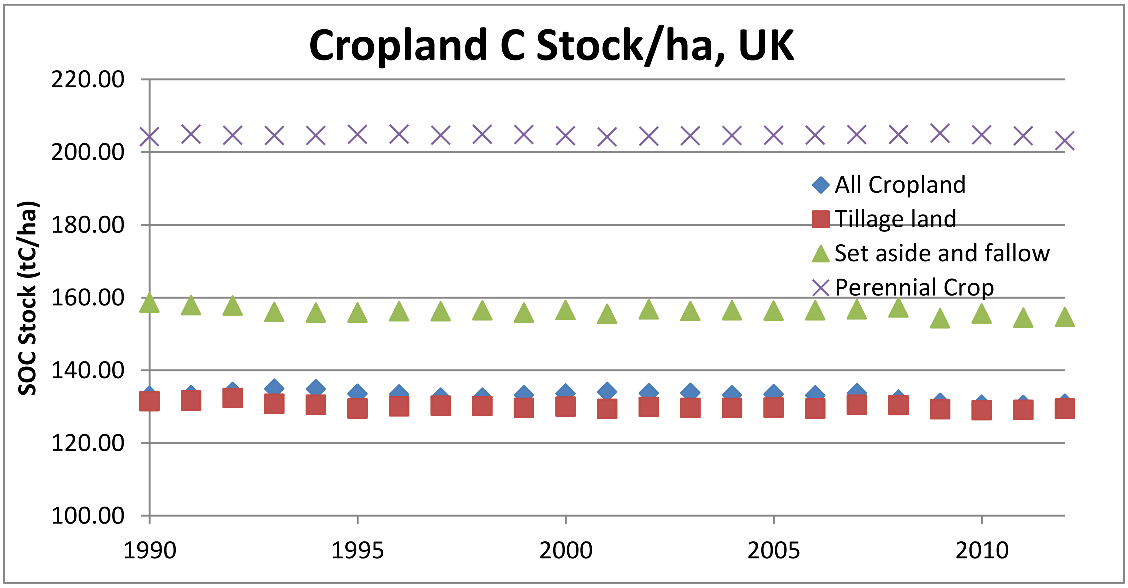

Figure 4.2 UK Cropland SOC Stocks per ha estimated using IPCC default stock change factors.

Within Cropland, tillage land is the largest store of SOC because of its large area. The SOC stock per hectare is highest for perennial crops, but because of the small area under perennial crops they make a small contribution to the total carbon store.

Reference conditions assume annual crops are conventional tillage and receive medium inputs; perennial crops are not tilled and receive medium inputs and set aside land is not tilled and receives low inputs. The change in SOC stock from these conditions estimates using the IPCC default stock change factors is shown in Figure 4.3.

As discussed in Section 4.1.4, modelled stock change factors suggest that using IPCC default stock change factors may overestimate the potential to increase carbon sequestration in UK Cropland soils due to management practices. There is a reduction in annual sequestration from land management from 2006 due to a reduction on the area of set aside which stores more carbon per hectare than tillage land.

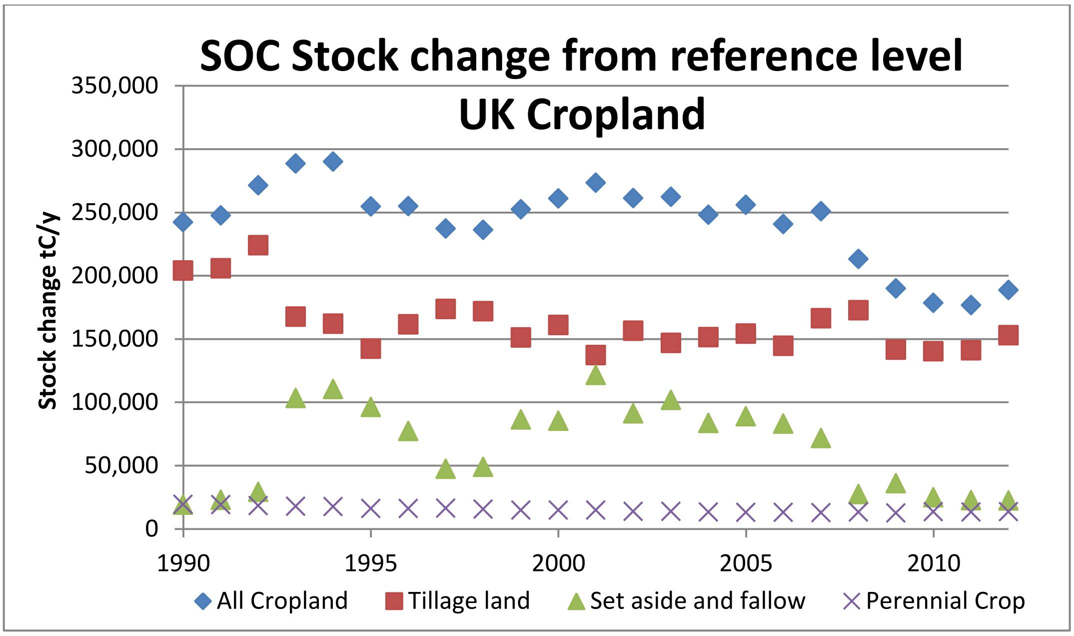

Figure 4.3 Change in UK Cropland stocks from reference levels due to land management.

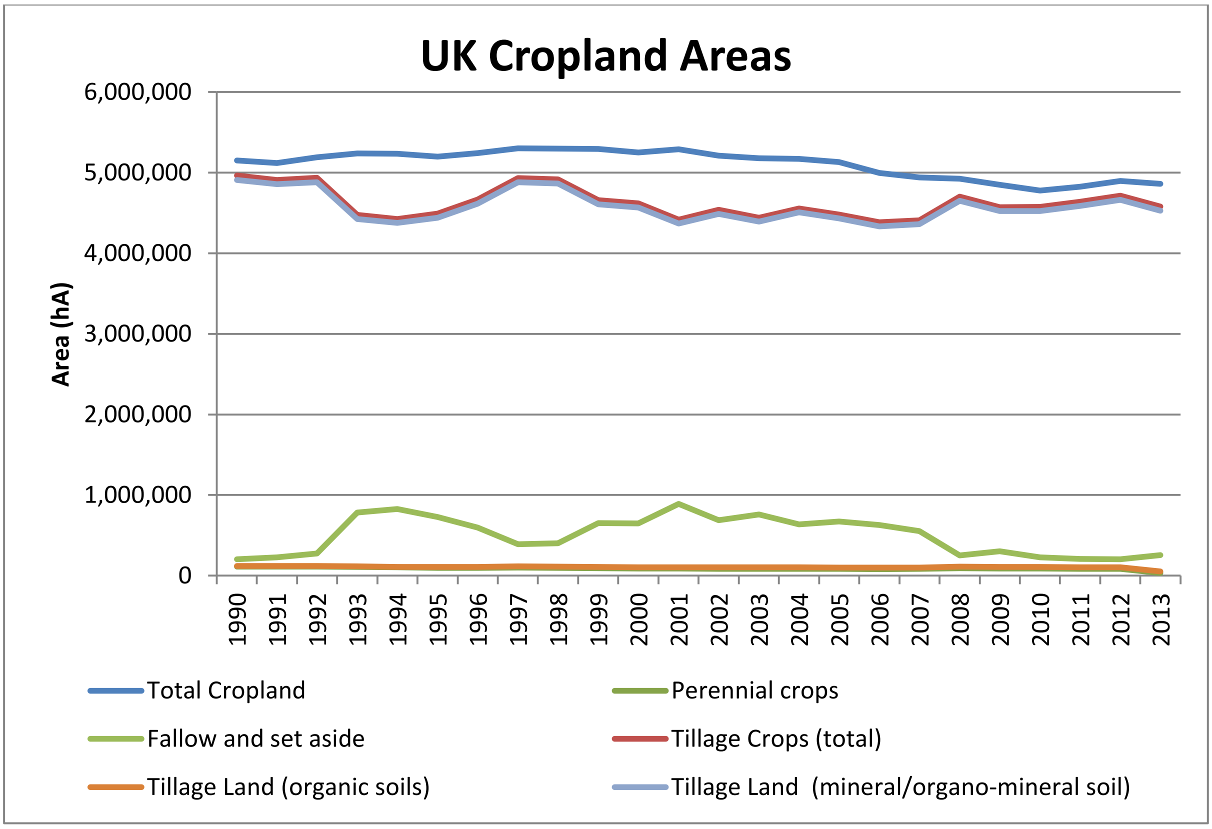

Figure 4.4 Areas under different Cropland types in the UK 1990 – 2013

The patterns of SOC stock change seen in Figures 4.1 - 4.3 are largely explained by conversion of tillage land to set aside between 1990 and 2008 as a result of EU agricultural policy. Figure 4.4 shows the change in areas of different types of Cropland. The trends in the areas of tillage land and set aside and fallow mirror the change in SOC stocks in land under these activities. The IPCC default factors assign higher SOC stocks to set aside and fallow land than tillage land. Therefore the main driver of change in carbon stocks under Cropland is change between the different land uses within this category rather than changes in the management practices applied to tillage land.

The effects of change in tillage land management such as changes to tillage regimes or inputs is very small compared to these changes between different types of Cropland, even using the IPCC stock change factors which are likely to over-estimate their effect.

4.2.2 SOC Stock changes from Grassland Management

Permanent Grasslands hold higher SOC stocks per hectare than Croplands. Several factors contribute to this including inputs of livestock manure and faeces; the absence of soil disruption due to cultivation and continuous vegetation cover with no periods of bare ground.

While SOC stocks are higher in Grassland than Cropland, it must be noted that permanent Grassland under a consistent management regime will be at equilibrium and therefore will not be losing or sequestering carbon. Carbon loss or sequestration only occurs as a result of a change in land use or management. On mineral and organo-mineral soils such changes in SOC stocks continue only until new equilibrium stocks are reached. This is in contrast with the situation for true organic soils in active peatlands which can continue to sequester carbon indefinitely or, if damaged by drainage can continue to lose carbon until only an organo-mineral soil remains.

This project only considered the effect of management of Grassland on mineral and organo-mineral soils. Management of Grassland on organic soils is outwith the scope of this project, but is the subject of the IPCC Wetlands Supplement (2013)

Assessing the effect of Grassland management on SOC stocks more problematic for four main reasons:

1) Defining improved Grassland. In this study improved Grassland was taken to mean land reported as Grassland > 5 years (permanent improved Grassland) and Grassland < 5 years (temporary/rotational improved Grassland) in the June agricultural censuses. IPCC guidelines suggest that rotational grass should be included in Cropland. However in the UK LULUCF inventory to date it has been included in the Grassland category. This is because the Countryside Survey land use data on which the land use change matrices are based which does not distinguish between temporary and permanent Grassland. There are plans to move to a vector based approach to tracking land use change for spatially referenced land parcels which will allow temporary and permanent Grassland to be separated. Rough grazing is considered to be nominally managed Grassland.
2) Assessment of C_{ref} for rotational Grassland. It is unlikely that that rotational Grassland will reach equilibrium SOC stocks. For rotational Grassland which spends most of the rotation cycle as Cropland C_{ref} values for Cropland may be more appropriate, while for Grassland

which spends most of the rotation cycle as Grassland, the Grassland C_{ref} value may be more appropriate. The work in Section 3 of this project shows that there are strong regional variations in rotation patterns, but at present full information on how these are distributed is not known, and therefore the proportional of rotation Grassland which spends most of the time under grass and the proportion which spends most of its time under crops is not known.

3) As discussed in section 4.1.4 above expert opinion is that the stock change factors of Grassland management in the IPCC 2006 Guidance may not be appropriate to the UK. In particular there are concerns about the stock change factor for Improved Grassland, which suggests that intensification via measures such as drainage, liming or fertilisation could increase SOC stocks. The literature concurs with this view for pasture Grassland, but there is a gap in the published research on the effect of intensification on rough grazing land on high carbon soils. Expert opinion is that the effect of intensification on rough grazing land would not be the same as intensification of lowland pasture on mineral soils, and could lead to release of SOC due to chemical oxidation and increasing soil respiration. Similarly, expert opinion was that allowing marginal improved pasture to revert to rough grazing might increase SOC stocks in practice, but this is not reflected in the IPCC default stock change factors.
   Using the IPCC default stock change factor intensive Grassland to assess SOC stock changes in UK Grassland could therefore give a perverse incentive for drainage, liming and fertilisation of organo-mineral upland soils.
4) Because of a lack of activity data on eroded Grassland soils it was not possible to account for degradation of Grassland.

Because of these issues, and in particular the uncertainty around the response of high carbon organo-mineral soils to intensification and reversion it was felt that presenting stock change data based on the IPCC default stock change factors for Grassland would be misleading.

4.3 Cropland Management Change Scenarios

Scenarios were developed to assess the potential of Cropland management to increase SOC stocks in order to mitigate climate change.

Because of the difficulties and data gaps associated with assessing changes in SOC stocks due to Grassland management no attempt was made to assess the potential to increase carbon sequestration in grassland through changes in land management.

For Cropland five management scenarios were examined. These all focussed on the management of tillage land rather than conversion between tillage land, perennial crops and set aside and fallow. The effect of each scenario was assessed using three different stock change factor options:

a) The IPCC default stock change factors (Table 1.1) These consider stocks to 1 m. (IPCC factors)

b) IPCC default stock change factors except using a factor of 1 for reduced tillage and no tillage to reflect the findings of the literature review and modelling work that tillage reduction may have little effect on SOC stocks in the UK. These consider stocks to 1 m. (IPCC Till =1 factors)

c) The stock change factors modelled by the DailyDayCent for tillage reduction and inputs.

The values used were the averages modelled for Rothamsted and the four experimental sites (Table 2.3). (DDC factors) It must be noted that these factors were modelled using data from a very limited number of sites only one of which had long term field data and therefore are likely to be highly uncertain. However they have been included to show that for at least some UK locations the mitigation potential of Cropland management practices may be considerable less than suggested by the IPCC default stock change factors. The model used to generate these factors only considered stocks to 23 cm, and therefore changes in stocks at depth not be reflected in these factors.

The effects of the five scenarios on SOC stocks per hectare calculated using the sets of stock change factors listed above are shown in Figure 4.5. These compare the effect of mitigation options with actual practice on Cropland in 2012. The small decrease SOC stock estimated using stock change factors modelled by the DDC model is due to the low stock change factors assigned to inputs and manure by DDC compared to the IPCC default values and therefore do not compensate for SOC losses due to land being under cultivation or set aside/fallow. However the modelled loss of SOC is very small and may not be significantly different from zero.

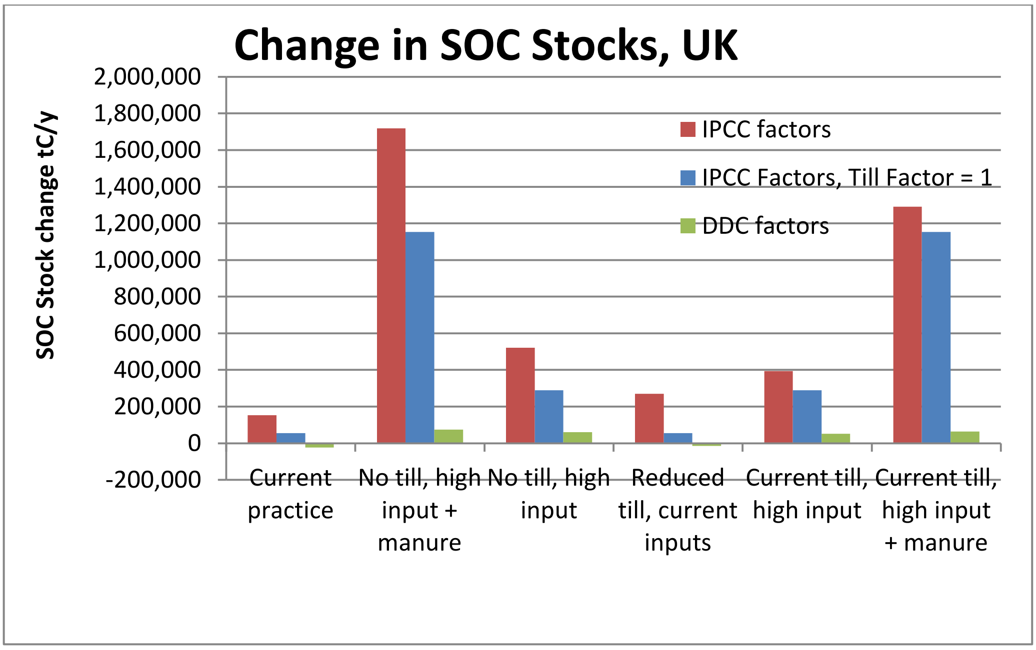

Figure 4.5 Effect of Cropland management scenarios on SOC stocks per hectare estimated using a) IPCC default stock change factors b) IPCC default stock change factors except for factors of 1 for no tillage and reduced tillage. c) Stock change factors modelled by DailyDayCent.

4.3.1 Scenario 1 – maximum SOC increase

Scenario 1 was intended to assess the maximum possible increase in SOC stocks due to Cropland management. This scenario assumed 100% of tillage was cultivated using zero tillage, and that all Cropland received high inputs plus manure.

This is known to be a highly unlikely scenario, but is included to show the maximum possible effect of land management on Cropland SOC stocks. To be effective in mitigating climate change increases in SOC would need to be weighed against increased nitrous oxide emissions from increased nitrogen inputs from fertiliser and manure and from compaction due to the zero tillage. Table 2.8 contains data from the LandscapeDNDC model which gives some indication of nitrous oxide emissions resulting from Cropland management intended to increase SOC stocks. In addition to nitrous oxide emissions which could outweigh the carbon dioxide reduction achieved by increased SOC sequestration, there would also be an issue of availability of sufficient quantities of manure or organic waste, as UK supplies are already almost fully utilised. Increasing livestock numbers in order to increase SOC stocks under Cropland would lead to increased methane emissions from ruminants and potentially require conversion of Grassland to Cropland to provide fodder and is therefore unlikely to reduce greenhouse gas emissions, although a full life cycle analysis to prove this has not been carried out.

The IPCC factors suggested the largest increase in SOC sequestration. The DDC modelled factors, which were lower for all management activities suggested only about tenth of this sequestration. Using IPCC Till =1 factors gave an intermediate result.

4.3.2 Scenario 2 – no tillage, high inputs

Scenario 2 assumed that all tillage land was managed with a no tillage regime and received high inputs as defined in the flow chart in Appendix 3.1 but no additional manure. Although slightly more realistic than Scenario 1, universal adoption of zero tillage is considered unlikely given that the proportion of UK land cultivated using this technique is currently small.

Using both the IPCC default factors and the IPCC Till = 1 factors there was a large decrease in mitigation potential moving from Scenario 1 to Scenario 2 reflecting the large effect of manure inputs to increases in SOC sequestration rates. Using the stock change factors from the DDC model the change between scenarios is less marked as this model suggested that manure inputs might be less effective at increasing SOC stocks under UK conditions than implied by the IPCC factors.

4.3.3 Scenario 3 – current manure and fertiliser inputs, reduced tillage

Scenario 3 assumed current inputs of manure and fertiliser, reflecting the constraints of the availability of manure and constraints on the use of mineral N fertiliser, but assumes all tillage is cultivated using reduced tillage techniques.

Using the IPCC factors suggests that this scenario might approximately double SOC sequestration rates compared to current tillage practice. As with current practice, the DDC factors suggest a slight loss of SOC which occurs. However this loss is very slightly less than for the current practice scenario because of the slight increase in SOC stock from reduced tillage modelled by DDC. As the IPCC Till = 1 factors show no effect of tillage reduction by definition, and in this scenario tillage is the only management practice which changes from current practice the stock change shown using these factors is the same as for current practice.

Adoption of reduced tillage cultivation over all of the UK's cropland area seems unlikely to happen in practice because of the need for periodic cultivation for weed control and to avoid compaction.

4.3.4 Scenario 4 – current tillage, high inputs

Scenario 4 assumes the current tillage regime, but with high inputs to all land as defined in the Appendix 3.1 Flow Chart. The IPPC factors suggest that the SOC sequestration rate approximately trebles. The IPPC Till = 1 factors suggest that SOC sequestration might double, and the DDC factors suggest a change from small SOC losses under current practice to SOC sequestration under the current tillage high input regime.

This scenario would be undesirable in practice because of the increased emissions of nitrous oxide and risk of nitrate run-off to watercourses.

4.3.5 Scenario 5 – current tillage, high input plus manure

Scenario 5 again assumes the current tillage regime, but high inputs plus manure application to all land. As with Scenario 4 this would be undesirable in practice because of the effects on nitrous oxide emissions and nitrate run-off.

Comparing Scenario 4 and 5 both the IPCC factors and IPCC Till =1 factors suggests the largest increase in SOC sequestration results from manure application. This effect is much less marked using the DDC factors, although these do suggest increasing inputs of fertiliser and manure changes Cropland soils from losing small amounts of SOC under current practice to sequestering some SOC.

The magnitude of the changes in SOC stocks per hectare resulting from changes in Cropland management practices are broadly in line with those found using DailyDayCent modelling (see Section 2.1.1)

Using these scenarios to assess the potential of Cropland management to increase SOC stocks leads to two main conclusions.

Firstly, there is still considerable uncertainty in what the stock change factors for UK conditions are. Although factors have been estimated using the DailyDayCent model these values are based on a very limited number of sites, only one of which has long term data. However, the DDC stock change factors, Landscape DNDC and the literature review suggest that the IPCC default stock change factors may overestimate the effect of Cropland management on carbon stocks in UK soils.

Secondly, even using the IPCC default stock change factors which are believed to overestimate the effect of management practices for the UK, the scenario modelling suggests that there is limited scope to increase Cropland SOC stocks through changes in land management practices, as extreme scenarios have limited effect on SOC stocks. This scope is further reduced if the DDC modelled factors are used.

Practical limitations are likely to greatly reduce the scope to increase SOC sequestration in Cropland soils compared to the scenarios investigated.

As found in the modelling work reported in Section 2 and in the literature review carried out for this project (Buckingham el al, 2013), increased manure use is likely to be the most effective way to increase SOC stocks. However, its applicability is limited by the availability of manure and the potential adverse impacts of the resulting increases in nitrogen inputs. While it might be possible to increase inputs of organic waste other that farmyard manure, supply is limited and is already almost fully utilised; there are competing demands for organic wastes to be used as a feedstock for anaerobic digestion, and regulations governing application of waste to land control what can be applied in order to prevent soil contamination.

Converting tillage land to perennial crops or fallow and set aside could also increase SOC stocks. However, there is limited demand for produce from perennial crops, so the scope to increase them is limited. Although increased production of biomass fuels might drive some conversion to perennial crops, the area involved is likely to be small compared to the total UK Cropland area. Increases in set aside would have to be weighed against other factors such as the need for food security, biomass fuels and forestry.

4.4 Issues and Improvement Opportunities

The work on integrating the effects of Cropland and Grassland management in the LULUCF inventory has shown that it is feasible to report on Cropland management using current data sources. This study did not use the modelled stock change factors as they were not available in time to be used, but they could be used for future reporting.

Implementing reporting of Grassland management proved more problematic. Key issues are treatment of rotational grass, the effect of intensification of grassland management, particularly the conversion between improved grassland and rough grazing and the availability of stock change factors which are appropriate to the UK.

The information gaps relating to Grassland management and some suggestions on how they might be filled are shown in the Table 4.3.

There is a clear need for better long term data on the effects of land management on SOC stocks under Grassland. However, obtaining information from long term monitoring is slow, expensive, can only be used at a small number of sites and tends to have high uncertainty. It is therefore not practical to use this approach to fill knowledge gaps on the long term effects of management changes, and alternative approaches have to be considered.

While surveys such as Countryside Survey can be used to provide information on SOC stocks under different managements they may not be good indicators of the effect of management change, as differences in typography and climate can be the cause of both the management regime and the soil characteristics. For example rough grazing tends to be located in cooler, wetter areas which favour the formation of higher carbon soils. One approach which might avoid this confounding effect is to survey soils on either side of linear features such as fences, tracks or ditches where there is different management on either side of the feature.

Using this approach it may not always be possible to date when the change in management occurred (e.g. when field drains were installed). Coupling measurement of soil parameters and SOC stock, bulk density and pH with ^{14}C dating could give an indication of when the SOC stocks on each side of the feature started to diverge. Combining data on SOC at adjacent sites with other datasets held in the UK Soil Observatory might also help to identify underlying drivers.

Table 4.3 Knowledge Gaps relating to Grassland Management

Practice	Effect on SOC	Comments	Knowledge Gaps	Gap filling measures
Drainage of organic soils (histosols) under Grassland	Loss	IPCC default stock change factor 0.25 tonnes/ha/y Tier 2 stock change factors are used for carbon loss from lowland drainage under cropland, but may not be appropriate for Grassland. Will be addressed when implementing Wetlands Supplement guidance. Stock change factors in the Wetland Supplement may not be appropriate for the UK.	UK relevant stock change factors. Area of drained histosols under Grassland	Natural England report NECR089 on upland peat condition assesses area of drained upland peat in England. Forthcoming Welsh Government project on drained peat areas. JHI work are developing a remote sensing technique to assess peat condition for Scottish Government. DECC Wetlands Supplement implementation project
Improvement by seeding with improved grass varieties and legumes.	Gain for intensively managed Grassland. Possible loss if semi-natural grassland converted to intensive Grassland	Literature suggests that seeding with higher yielding grass species and legumes can increase SOC stocks, especially for low carbon soils. Little evidence of effect of conversion of semi-natural Grassland. Ploughing in order to reseed involves soil disturbance and could lead to loss of SOC.	UK relevant stock change factors for improving existing pasture and conversion of semi-natural grassland to pasture. Information on the effect of soil disturbance when seeding.	Needs field measurements to assess effect of conversion between improved pasture and semi-natural Grassland. Welsh Government project being developed to examine the effect of intensification/reversion on SOC stocks. Activity data could be obtained from agricultural census areas for permanent grass and rough grazing, although rough grazing does not include semi-natural grass which does not receive CAP payments. Would need to develop a land use change matrix within the Grassland category of the inventory to capture this.
Inputs of mineral N	Depends on Grassland type.	Mineral fertiliser can boost SOC in some cases by promoting grass growth and inputs of root exudates and residues to soil. Literature suggests that the effect will depend on Grassland type and nutrient status. May increase SOC on Grassland where growth is nutrient limited, but effect less clear elsewhere. Limited evidence on the effect of N inputs to SOC under semi-natural Grassland. Implications of increased N inputs on N_2O emissions and nitrate run off need to be considered.	Stock change factors for different grassland types. Activity data.	Literature suggests that response of Grassland SOC to mineral N inputs is less than to inputs of organic manures. Stock change factors for mineral N inputs to Cropland are being modelled as part of the current project. Assumption is that semi-natural Grassland does not receive mineral N. The Agricultural inventory uses crop-specific application rates combined with crop areas than from the June census returns. Field data needed to assess effect of intensification.

Practice	Effect on SOC	Comments	Knowledge Gaps	Gap filling measures
Inputs of manure, slurry	Gain	In addition to supplying N, manures and slurries provide direct additions of carbon. All literature suggests that this increases SOC, although effect is greatest for lower carbon soils. Manure and slurry are spread on improved pasture close to livestock housing, and are unlikely to be spread on seminatural grassland. Land may already have equilibrium SOC stocks for this. Most manure and slurry stocks are currently spread to land, although some is used in biogas digestors. There is limited scope to increase inputs. The relative benefits of using manure and slurry for biogas production need to be weighed against potential to increase SOC.Manure and slurry inputs providing N in excess of plant requirements can increase N_2O emissions and nitrate run off.	UK specific stock change factors. Detailed activity data.	IPCC default factors available. Stock change factors for manure application to Cropland are being modelled as part of the current project. These may be transferable to Grassland. Areas receiving manure are available in British Survey of Fertiliser Practice, although this does not give application rates. Methodology used should be consistent with Agricultural Inventory.
Inputs of other organic waste	Gain	Use of organic waste other than manure and slurry has not been considered in detail in the current project. Issues are likely to be broadly similar to manure and slurry use, but the additional need to consider potential contaminants in the waste. There will also be some emissions from transportation of the waste to land. There may be some potential to reduce emissions from landfills.	Stock change factors. Activity data	Stock change factors for some wastes (e.g. sewage sludge) may be similar to livestock manures. Activity data on sites receiving organic waste should be available from environment agencies waste licencing records. Records of sites receiving sewage sludge should be available from records kept by sludge producers to comply with the Sludge (Use in Agriculture) Regulations, which is the approach used for the Agricultural Sector of the Inventory.

Practice	Effect on SOC	Comments	Knowledge Gaps	Gap filling measures
Stocking level	Depends on Grassland type.	Stocking level is linked to several other management practices, as increased stocking levels require higher grass yields. Higher livestock numbers will increase manure and N returns to pasture, but reduce plant residue returns and may increase erosion. Increasing ruminant numbers will increase methane emissions. The practice of mob grazing has not been considered in the current project due to lack of published literature for UK relevant conditions.	Lack of stock change factors for effect of stocking on different Grassland types.	This activity links to a number of others, which have more direct effects on SOC, so probably best to consider these rather than stocking levels as such. Field data needed to assess the effect of intensification on rough grazing and pasture.
Liming.	Depends on Grassland type.	Liming intensively managed Grassland may increase SOC by improving grass yields. Liming Grassland where soil microbial activity is inhibited by acidifying will increase SOC losses. LULUCF inventory currently includes emission from carbonate in lime which is assumed to be applied to permanent and rotational grass only, not rough grazing.	Lack of stock change factors for different types of Grassland.	Assumption is that lime is not applied to semi-natural Grassland. There are no IPCC default stock change factors for this. It may be possible to model the effect of lime addition to improved Grassland, although long term data to calibrate and validate models is limited. Field data needed, especially to assess the effect of raising the pH of rough grazing on organo-mineral soils.
Degradation leading to soil loss.	Loss	Soil erosion leads to loss of SOC, however the fate of the carbon in eroded material is not clear. It may be redeposited rather than oxidised.	Lack of knowledge on the fate of C in eroded soil. Lack of activity data	Natural England report NECR089 on upland peat condition assesses area of eroded upland peat in England. SNH have commissioned several reports dealing with soil erosion (Commissioned reports 054, 325, and 410). Report 325 also covers NI.
Grassland-Cropland rotation pattern.	Depends of rotation pattern.	This project has attempted to use IACS data to establish rotation patterns for UK regions. However this will not give information on the effect of rotation pattern on SOC stock.	Rotation patterns. Stock change factors.	Some information on rotation patterns has been obtained for England and Wales using IACS data. However delays in obtaining the data have meant that this work is behind schedule. IACS data for Scotland and NI should be available shortly, and further work to assess rotation patterns will be carried out.
Managed burning of heather moorland.	Loss?	Uncontrolled burn in wildfire is known to oxidise soil C. There is a view that controlled burns do not affect SOC stocks, but measurements are limited, and results are contradictory.	Lack of stock change factors. Activity data	CEH have a PhD project on heather management which considers its effect on carbon fluxes. This is currently being written up and may shed some light on the effect on SOC stocks, although this is not the main focus of this project.

There is a need for complete data on soil erosion for all UK administrations. Some studies have piloted remote sensing techniques to map this. Improved data on peatland erosion would also be useful for implementing the reporting required for the Wetlands Supplement.

The SP1113 international comparison on reporting Grassland management found that most countries are only able to report on a limited number of management activities at present. The practice most commonly reported is the effect of different broad categories of Grassland on SOC stocks. Several countries include emissions from drained organic soils.

While the UK has more complete data on land management practices than many other EU countries which could be fed in to reporting on Grassland management, the degree of detail used should be proportionate to the likely emission or removal. Similarly, the effort devoted to plugging knowledge gaps should be proportionate to the likely effect that the practice has on SOC stocks, although in some cases the lack of data makes this difficult to assess. Reporting on Grassland management therefore needs to balance the need for detail and completeness against the resource required and the size of the emission/removal.

Better understanding of the patterns of grass/crop rotations across the UK will be developed using IACS data which will be available shortly. It might also be possible to extend the initiative to use a vector approach to assessing land use change in the UK LULUCF inventory to develop vectors for grass/crop rotations, although IACS data are likely to give more detailed information than the remotely sensed data being used to develop land use change vectors.

5 Conclusions

This study has shown that it is possible to implement reporting on change in SOC stocks due to Cropland management in the UK LULUCF inventory, but has found that reporting on Grassland management will be more difficult due to data gaps and other issues discussed below.

Change in SOC stocks in Cropland has been modelled using the DailyDayCent (DDC) and Landscape DNDC (LDNDC) models, although the very limited data available to calibrate the models means that it may not be valid to apply these results across the UK. The DDC and LDNDC models agreed on the direction of change SOC stock likely to result from the key management practices, although they varied in the magnitude of the changes modelled. Stock change factors estimated using DDC suggested that the IPCC default stock change factors may over-estimate the change in SOC stocks resulting from change in Cropland management practices under UK conditions.

Change between different Cropland land uses give the largest changes in SOC stocks. EU incentives between 1992 and 2008 to convert tillage land to set aside are the main driver for change in SOC stocks under Cropland in the last 25 years. While a return to such policies could increase SOC stocks this would need to be balanced against other objectives such as food security and biofuel production, and therefore is unlikely to be applied on a large scale. CAP greening measures could have some role in encouraging changes in Cropland use and management to enhance SOC stocks. Similarly there is likely to be limited scope to increase the area under perennial crops although increased production of biomass fuels might drive some conversion.

Increasing manure inputs to Cropland would be the most effective way of increasing SOC stocks under tillage land. However, the scope to do this is constrained by the availability of manure. Other organic wastes could be used to supplement farmyard manure, but their use is regulated to avoid soil contamination. Increasing inputs of nitrogen fertiliser would be unlikely to have a net benefit on greenhouse gas emissions if nitrous oxide emissions are considered. Changing the tillage regime only gives limited benefit, and the scope to reduce tillage on UK Cropland appears to be small.

Overall Cropland management can contribute to increasing SOC stocks in mineral soils under Cropland, but the contribution is likely to be small, especially as the IPCC default stock change factors appear to over-estimate the effect of changes in land management under UK conditions. Other activities covered by the LULUCF inventory such as land use change and management of organic soils are likely to have greater effects.

Reporting on Grassland management has proved more difficult due to lack of data on soil erosion, grass/crop rotation cycles and the effect of intensification. Although activity data exists which would allow estimation of the effect of Grassland management using the IPCC default emission factors, it was judged that this could be misleading and therefore no such estimates are reported from this project.

Suggestions for strategies for filling the data gaps which are currently preventing reporting of changes in SOC stocks under Grassland are given in Section 4.4. A key need is for field data on the effect to intensification practices, particularly when applied to marginal pasture and rough grazing on organo-mineral soils.

IACS data has been used to elucidate grass/crop rotation practices. Because of delays in obtaining the data only English and Welsh data has been processed. It has been possible to develop matrixes of change between Grassland and Cropland and map the results. As the data processing framework has now been established it would be relatively straightforward to incorporate this approach into annual LULUCF reporting to give a better representation of Cropland/Grassland “churn”.

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Appendix 1 Summary of other countries' reporting of Cropland and Grassland management practices.

	Management activities elected under the Kyoto Protocol		Reporting of categories 5B and 5C in the CRF under the UNFCCC		Cropland management activities reported	Grassland/Grazing land management activities reported
Party	**Cropland**	**Grazing land**	**5B Cropland**	**5C Grassland**		
Australia			**x**	x	Crop type **AD** Remote sensing **SCFs** Modelled based on crop/climate zones	Grass vs scrub **AD** Remote sensing **SCFs** Modelled based on crop/climate zones
Austria			x	x	Crop type – annual vs perennial (vines, horticulture, garden,energy crops, Christmas trees). Tillage, manure. **AD** IACS, Census **SCF** T1 (some T2 from literature)	One cut meadows, two or more cuts, litter meadows, cultivated pasture, rough pasture, alpine pasture, abandoned pasture. **AD** IACs, Census **SCF** T1/2
Canada	x		x		Tillage and annual vs perennial, summer fallow, cultivation of organic soils Census data **AD** MARS reporting system, census. **SCFs** CENTURY model	
Denmark	x	x	x	x	Annual vs perennial and hedgerows, cover crops, manure. **AD** IACS, census, aerial photos (hedges) **SCFs** CTool (mineral), T2 (organic)	Drained organic soils **AD** IACS, census **SCF** T1
Finland			x	x	Tillage, inputs (organic farms = high) fallow, liming **AD** Survey, census, expert judgement (till) **SCF** T1 (mineral), T2 (organic)	No practices affecting SOC stocks.
Germany			x	x	Drained organic soil **AD** Survey, CORINE **SCF** T2	Drained organic soil, **AD** Survey, CORINE **SCF** T2

	Management activities elected under the Kyoto Protocol		Reporting of categories 5B and 5C in the CRF under the UNFCCC		Cropland management activities reported	Grassland/Grazing land management activities reported
Party	**Cropland**	**Grazing land**	**5B Cropland**	**5C Grassland**		
Ireland			x	x	Only reports practices affecting biomass stocks, not SOC stocks. **AD** CORINE, IACS, survey **SCF** T1	Grassland type – Pasture, Natural grass, rough grazing Drained organic soil. **AD** CORINE, IACS **SCF** T1
New Zealand			x	x	Annual (long term cultivated, low input), vs perennial (long term cultivated, no till, high input); drained organic soils. **AD** Remote sensing **SCF** T1	High producing (improved, high input) , low producing (improved medium input), woody; drained organic soils. **AD** Remote sensing **SCF** T1
Portugal	x	x	x	x	Crop types; annual rain fed crop, annual irrigated crop, rice, vines, olives and other permanent crops. Tillage reduction. **AD** IACs, census data **SCFs** T2	Biodiverse pasture with legumes. **AD** IACs, census data **SCFs** T2
Spain	x				In Spanish	
Sweden			x	x	No practices affecting SOC stocks.	No practices affecting SOC stocks.
United Kingdom			x	**x**	Lowland drainage **AD** Bradley 1997 matrix **SCFs** T1	No practices affecting SOC stocks.

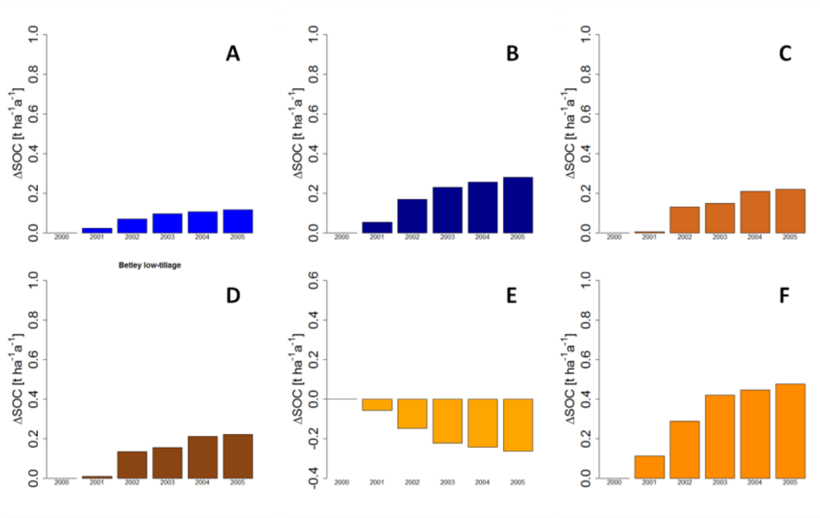
Appendix 2.1 : Parameters of the different soil types on the test/experimental sites used in modelling stock change factors.

	Rothamsted	Betley	Terrington	Boxworth	Middleton
soil type	sandy silt loam	sandy loam	silty clay loam	clay	loam
sand [%]	25.1	67	8	21	34
clay [%]	25.2	8	32	51	20
bulk density [g/cm3]	1.08	1.09	1.38	1.2	0.93
pH	7.35	6.5	8.1	8.2	7.5
Field capacity [% v/v]	20.7	20.7	36.6	46.0	29.0
Wilting point [% v/v]	14.4	9.5	20.8	24.6	10.2

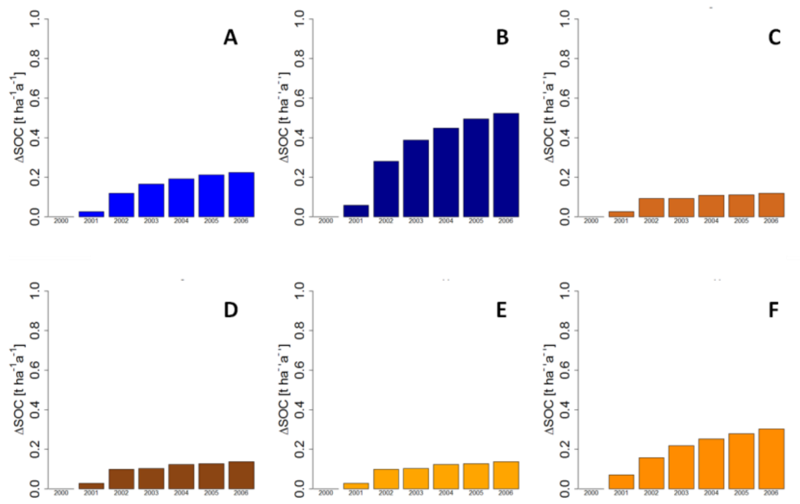
Appendix 2.2: Daily DayCent SOC stock changes for the Betley, Middleton, Boxworth and Terrington test sites for the different mitigation options

(A: removal of 30 % residues; B: no residue removal; C: no tillage; D: less intensive tillage; E: half amount of manure; F: double amount of manure).

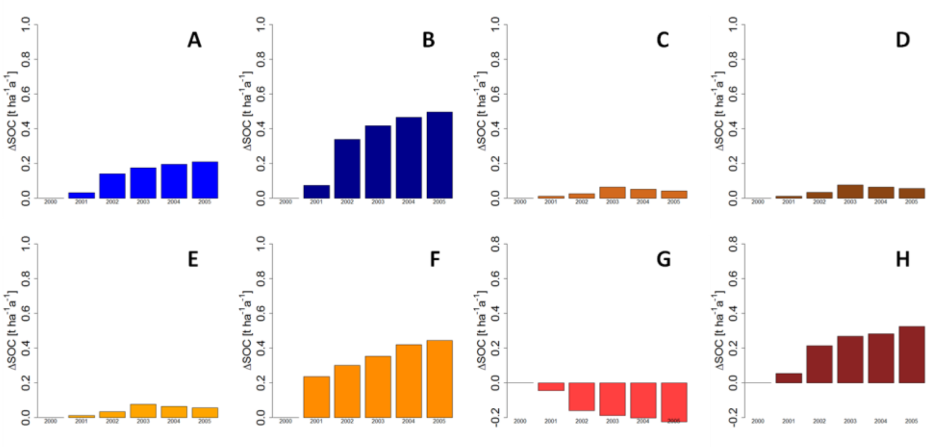
Betley



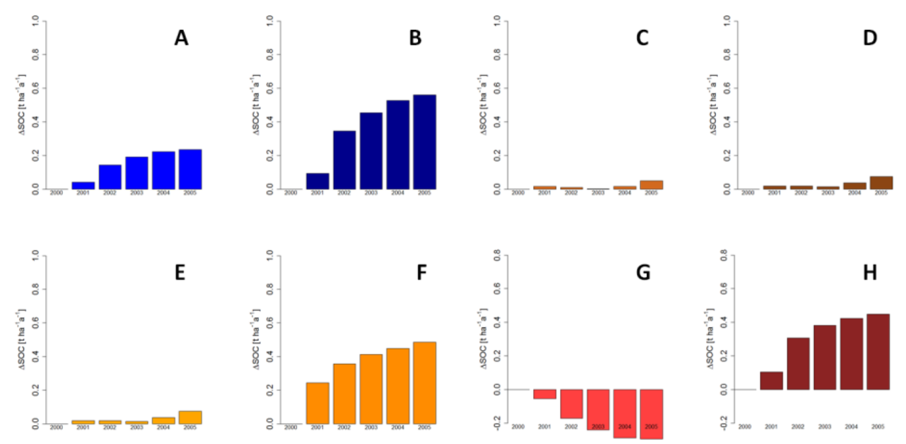
Middleton



Boxworth



Terrington



Appendix 2.3 Landscape DNDC Model Validation

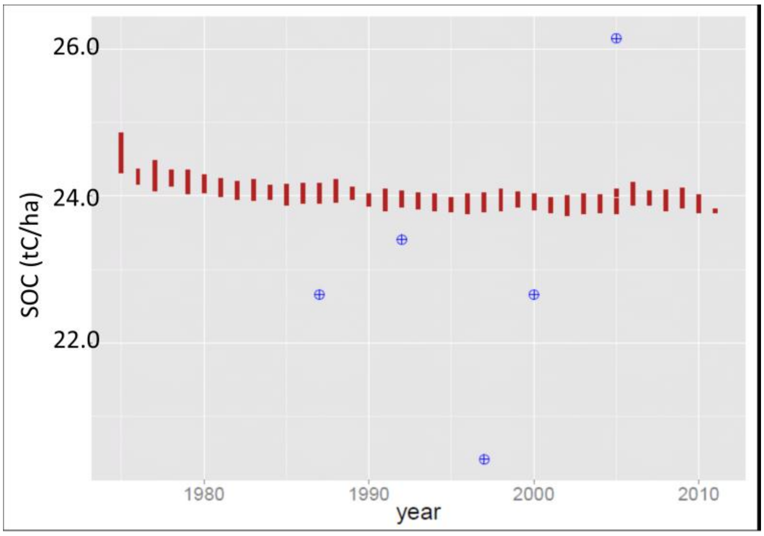


Figure A2.3.1 Validation for Plot 8 Rothamsted (AN fertilisation) Blue dots show measured soil carbon stocks from Rothamsted field experiment for an ammonium nitrate fertilised plot. Red bars show Landscape-DNDC modelled SOC stocks for the Rothamsted plot (1975 to 2010).

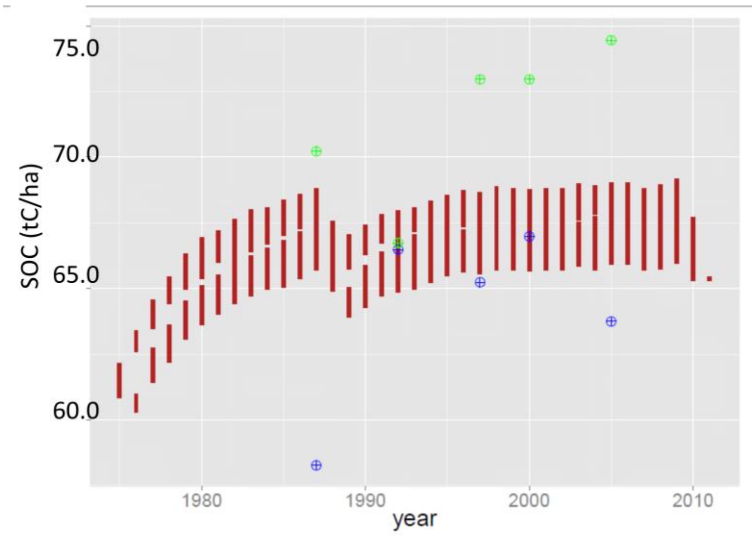


Figure A2.3.2 Model validation: Modelled daily soil carbon and measured soil carbon for manure Plots 21 and 22 (Rothamsted dataset) . Blue and green dots show measured are soil carbon stocks for two manure fertilized plots (with the same soil characteristics) from Rothamsted field experiment. Red bars show Landscape-DNDC modelled SOC stocks for the Rothamsted manure-fertilized plots (1975 to 2010).

Appendix 2.4: Landscape DNDC Scenario Outputs – SOC Stock Tables

Year	Scenario										
	Baseline	**R30**	**R50**	**T0**	**T10**	**F +50**	**F -50**	**AN**	**AN+M**	**AN**	**AN+M-50**
		1	2	3	4	5	6	7	8	9	10
1970	24.16	24.16	24.16	24.16	24.17	24.16	24.16	24.16	25.56	24.16	24.85
1971	23.99	24.10	23.89	24.01	24.00	24.00	23.99	23.99	26.25	23.99	25.13
1972	23.90	24.15	23.70	23.96	23.92	23.99	23.88	23.89	26.62	23.89	25.26
1973	23.91	24.32	23.57	24.03	23.95	23.90	23.82	23.89	27.11	23.90	25.50
1974	24.01	24.62	23.58	24.15	24.06	23.90	23.89	23.99	27.43	24.00	25.71
1975	24.01	24.65	23.89	24.16	24.08	24.06	23.85	23.98	26.38	23.99	25.87
1976	24.00	24.64	24.14	24.18	24.07	24.19	23.81	23.96	27.12	23.98	25.90
1977	24.00	24.71	24.61	24.23	24.08	24.26	23.79	23.96	27.30	23.98	25.85
1978	24.02	24.78	24.99	24.27	24.10	24.33	23.80	23.98	27.63	24.00	25.94
1979	24.11	24.99	25.53	24.35	24.18	24.43	23.91	24.07	27.83	24.09	26.04
1980	24.06	24.88	25.50	24.27	24.12	24.39	23.84	24.02	27.91	24.04	25.98
1981	24.07	24.92	25.64	24.27	24.14	24.44	23.82	24.03	27.98	24.05	25.98
1982	24.06	24.92	25.77	24.26	24.11	24.46	23.83	24.02	27.96	24.04	25.93
1983	24.08	24.96	25.92	24.28	24.13	24.52	23.85	24.04	28.08	24.06	25.99
1984	24.07	24.97	26.02	24.28	24.12	24.50	23.85	24.03	28.13	24.05	26.00
1985	24.06	24.95	26.01	24.28	24.12	24.48	23.83	24.02	28.09	24.04	25.97
1986	24.13	25.04	26.20	24.34	24.18	24.55	23.89	24.09	28.17	24.11	26.03
1987	24.12	24.99	26.11	24.32	24.17	24.54	23.85	24.07	28.16	24.10	25.99
1988	24.07	24.90	25.97	24.25	24.12	24.47	23.80	24.02	28.05	24.05	25.92
1989	24.12	24.99	26.10	24.26	24.17	24.53	23.78	24.07	28.34	24.10	26.07
1990	24.04	24.87	25.84	24.25	24.09	24.47	23.71	23.99	28.28	24.02	25.99
1991	24.06	24.92	25.96	24.32	24.11	24.48	23.76	24.02	28.28	24.04	26.00
1992	24.07	24.89	25.84	24.30	24.12	24.53	23.73	24.01	28.11	24.04	25.89
1993	24.05	24.84	25.79	24.26	24.09	24.58	23.72	23.99	28.05	24.02	25.85
1994	24.02	24.80	25.77	24.23	24.05	24.52	23.71	23.96	28.02	23.98	25.83
1995	24.01	24.81	25.69	24.23	24.05	24.50	23.67	23.95	28.15	23.98	25.87
1996	24.06	24.91	25.91	24.34	24.10	24.54	23.75	24.01	28.45	24.03	26.05
1997	24.02	24.79	25.74	24.31	24.08	24.48	23.71	23.96	28.25	23.99	25.91
1998	23.97	24.71	25.62	24.26	24.03	24.48	23.67	23.92	28.12	23.94	25.83
1999	23.93	24.64	25.47	24.20	23.98	24.43	23.63	23.88	27.96	23.90	25.73
2000	23.92	24.66	25.58	24.21	23.98	24.44	23.66	23.88	27.91	23.90	25.73
2001	23.91	24.62	25.49	24.20	23.97	24.40	23.64	23.87	27.76	23.89	25.64
2002	23.90	24.58	25.48	24.16	23.96	24.37	23.62	23.85	27.70	23.87	25.59
2003	23.96	24.66	25.52	24.22	24.02	24.47	23.65	23.91	28.19	23.93	25.84
2004	23.94	24.66	25.52	24.24	24.00	24.48	23.65	23.90	27.95	23.92	25.73
2005	23.94	24.68	25.52	24.22	24.00	24.46	23.64	23.90	27.86	23.92	25.68
2006	23.96	24.70	25.56	24.23	24.02	24.44	23.65	23.91	27.75	23.93	25.65
2007	23.87	24.55	25.39	24.14	23.94	24.34	23.60	23.83	27.67	23.85	25.58
2008	23.89	24.57	25.43	24.16	23.95	24.40	23.62	23.85	27.69	23.87	25.61
2009	23.91	24.57	25.45	24.15	23.96	24.44	23.63	23.87	27.69	23.89	25.61

Table A2.4.1 SOC stocks (tC/ha) including initialisation phase for each scenario (1970-2010) at 10 g/kg initial soil carbon. These data are displayed graphically in section 2.2.1

Year	Scenario										
	Baseline	**R30**	**R50**	**T0**	**T10**	**F +50**	**F -50**	**AN**	**AN+M**	**AN**	**AN+M-50**
		1	2	3	4	5	6	7	8	9	10
1970	60.43	60.43	60.43	60.43	60.44	60.43	60.43	60.43	61.86	60.43	61.15
1971	59.86	59.98	59.70	59.90	59.90	59.86	59.86	59.86	62.15	59.86	61.03
1972	59.36	59.64	59.20	59.43	59.41	59.44	59.36	59.36	62.13	59.36	60.77
1973	59.08	59.51	58.85	59.19	59.13	59.03	59.01	59.07	62.35	59.08	60.73
1974	58.97	59.61	58.83	59.10	59.03	58.86	58.88	58.97	62.45	58.97	60.73
1975	58.81	59.49	58.98	58.97	58.88	58.85	58.69	58.79	61.27	58.80	60.75
1976	58.67	59.36	59.07	58.89	58.76	58.89	58.54	58.64	61.90	58.65	60.67
1977	58.57	59.32	59.33	58.84	58.66	58.83	58.41	58.54	61.97	58.55	60.51
1978	58.52	59.31	59.59	58.81	58.61	58.83	58.34	58.49	62.22	58.51	60.52
1979	58.56	59.47	60.08	58.84	58.65	58.88	58.40	58.53	62.36	58.55	60.56
1980	58.47	59.31	59.99	58.72	58.55	58.80	58.28	58.43	62.39	58.45	60.45
1981	58.45	59.32	60.08	58.69	58.53	58.83	58.23	58.41	62.42	58.43	60.41
1982	58.42	59.30	60.17	58.65	58.49	58.83	58.21	58.38	62.37	58.40	60.33
1983	58.43	59.33	60.31	58.65	58.49	58.87	58.21	58.40	62.47	58.41	60.38
1984	58.41	59.32	60.38	58.64	58.47	58.84	58.20	58.37	62.50	58.39	60.37
1985	58.39	59.29	60.36	58.62	58.46	58.81	58.17	58.36	62.45	58.37	60.32
1986	58.46	59.37	60.54	58.68	58.52	58.87	58.22	58.42	62.53	58.44	60.38
1987	58.44	59.32	60.45	58.65	58.50	58.86	58.18	58.39	62.50	58.42	60.33
1988	58.39	59.21	60.30	58.57	58.44	58.79	58.12	58.34	62.38	58.36	60.24
1989	58.44	59.30	60.43	58.59	58.49	58.84	58.10	58.38	62.66	58.41	60.39
1990	58.35	59.19	60.17	58.57	58.41	58.78	58.03	58.31	62.60	58.33	60.31
1991	58.37	59.23	60.28	58.64	58.43	58.80	58.08	58.33	62.60	58.35	60.32
1992	58.39	59.20	60.17	58.62	58.43	58.84	58.04	58.33	62.42	58.35	60.21
1993	58.37	59.15	60.11	58.57	58.40	58.89	58.03	58.30	62.37	58.33	60.17
1994	58.33	59.11	60.09	58.54	58.37	58.84	58.02	58.27	62.34	58.30	60.15
1995	58.33	59.12	60.00	58.54	58.36	58.81	57.99	58.27	62.46	58.29	60.19
1996	58.38	59.23	60.22	58.65	58.42	58.85	58.07	58.32	62.76	58.34	60.36
1997	58.33	59.10	60.05	58.62	58.39	58.79	58.02	58.27	62.56	58.30	60.23
1998	58.29	59.02	59.93	58.57	58.34	58.79	57.99	58.23	62.43	58.25	60.14
1999	58.24	58.95	59.79	58.51	58.29	58.75	57.94	58.19	62.27	58.21	60.05
2000	58.24	58.97	59.90	58.52	58.29	58.76	57.97	58.19	62.22	58.21	60.04
2001	58.23	58.93	59.80	58.51	58.28	58.71	57.95	58.18	62.07	58.20	59.95
2002	58.21	58.90	59.79	58.48	58.28	58.68	57.93	58.16	62.01	58.18	59.90
2003	58.27	58.97	59.83	58.53	58.33	58.79	57.96	58.22	62.50	58.24	60.15
2004	58.25	58.97	59.83	58.55	58.31	58.79	57.96	58.21	62.25	58.23	60.04
2005	58.25	58.99	59.83	58.53	58.32	58.77	57.95	58.21	62.16	58.23	59.99
2006	58.27	59.01	59.87	58.55	58.33	58.75	57.96	58.22	62.06	58.25	59.96
2007	58.19	58.87	59.70	58.45	58.25	58.66	57.91	58.14	61.98	58.16	59.89
2008	58.21	58.88	59.74	58.47	58.27	58.72	57.94	58.16	62.00	58.18	59.91
2009	58.22	58.88	59.76	58.46	58.27	58.75	57.94	58.18	62.00	58.20	59.92

Table A2.4.2 SOC stocks (tC/ha) including initialisation phase for each scenario (1970-2010) at 20 g/kg initial soil carbon. These data are displayed graphically in section 2.2.1

Appendix 2.5: Landscape DNDC Scenario Outputs – CO_2 Flux

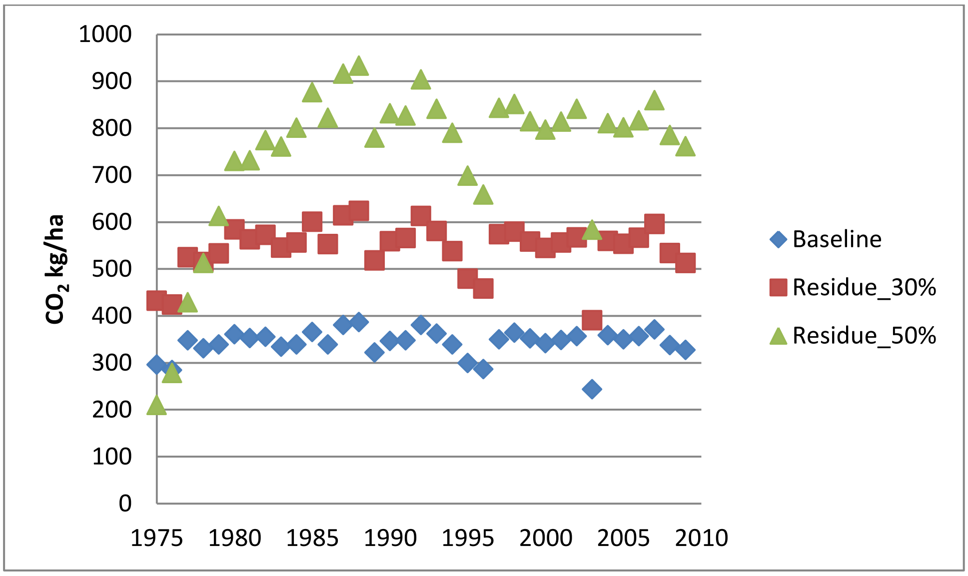


Figure A2.5.1 Modelled CO_2 flux for residue returns of Baseline (15%), 30% and 50% residue returns at 10 g/kg C initial SOC

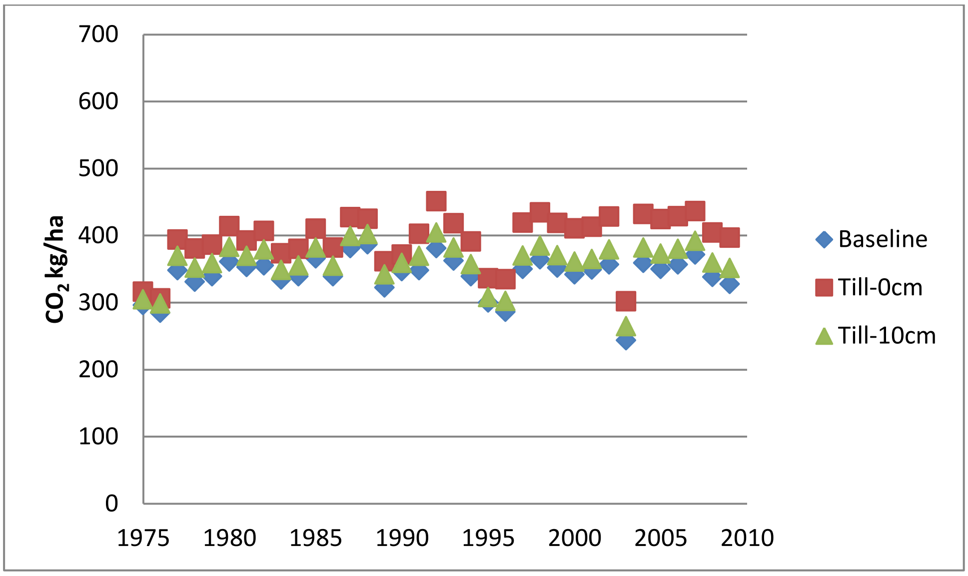


Figure A2.5.2 Modelled CO_2 flux for tillage regime of Baseline, 0 cm and 10cm tillage depth at 10 g/kg C initial SOC

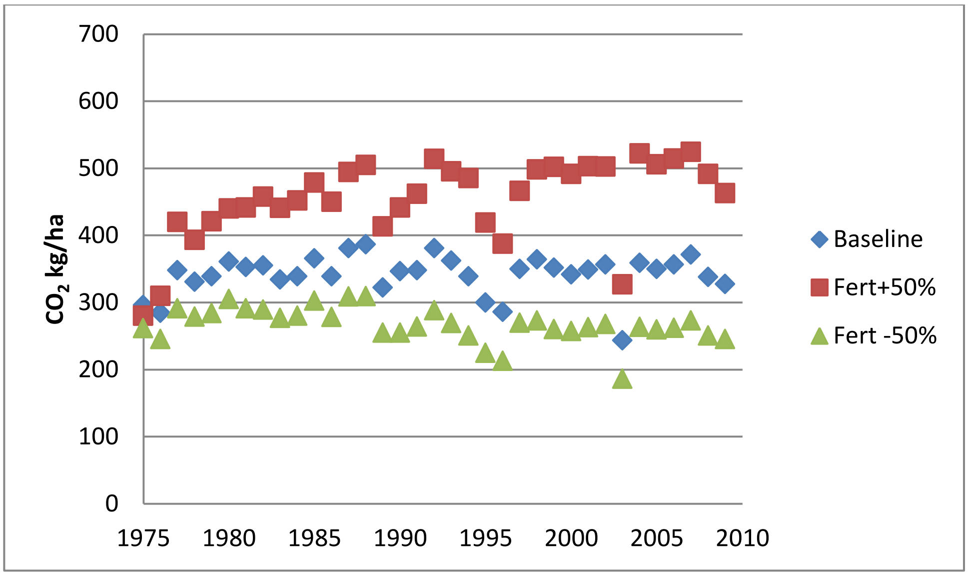


Figure A2.5.3 Modelled CO_2 flux for fertiliser applications of Baseline (210 kg N/ha), +50% additions (315 kg N/ha) and -50% fertiliser application (105 kg N/ha) at 10 g/kg C initial SOC

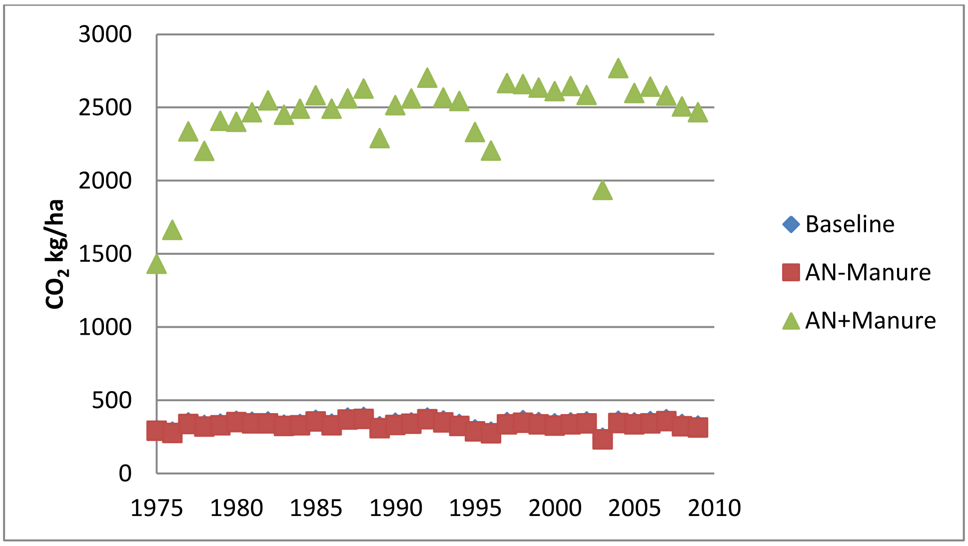


Figure A2.5.4 Modelled CO_2 flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (193 kg N/ha) and AN and manure application at 363 kg N/ha (193 kg AN/ha and 170 kg Manure/ha) at 10 g/kg C initial SOC

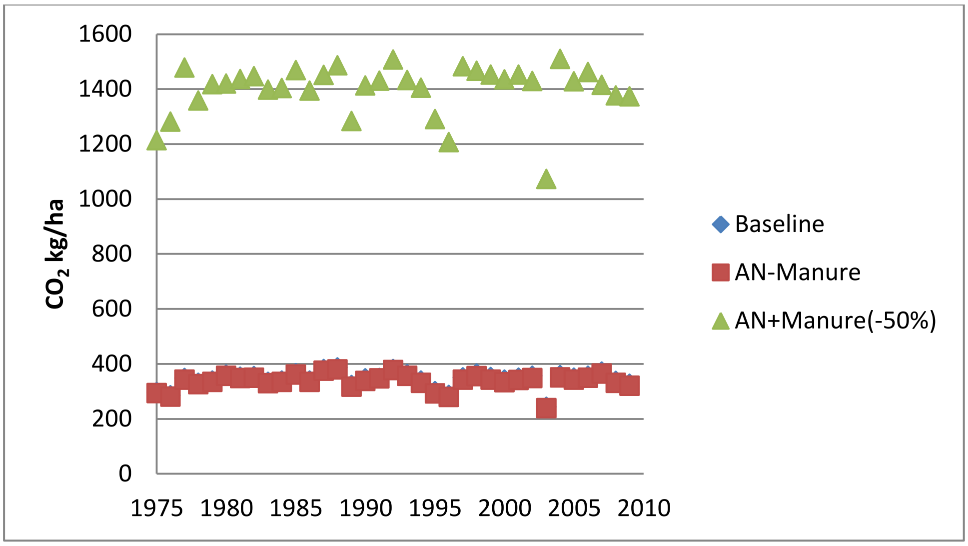


Figure A2.5.5 Modelled CO_2 flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (201 kg N/ha) and AN and manure application at 286 kg N/ha (201 kg AN/ha and 85 kg Manure/ha) at 10 g/kg C initial SOC

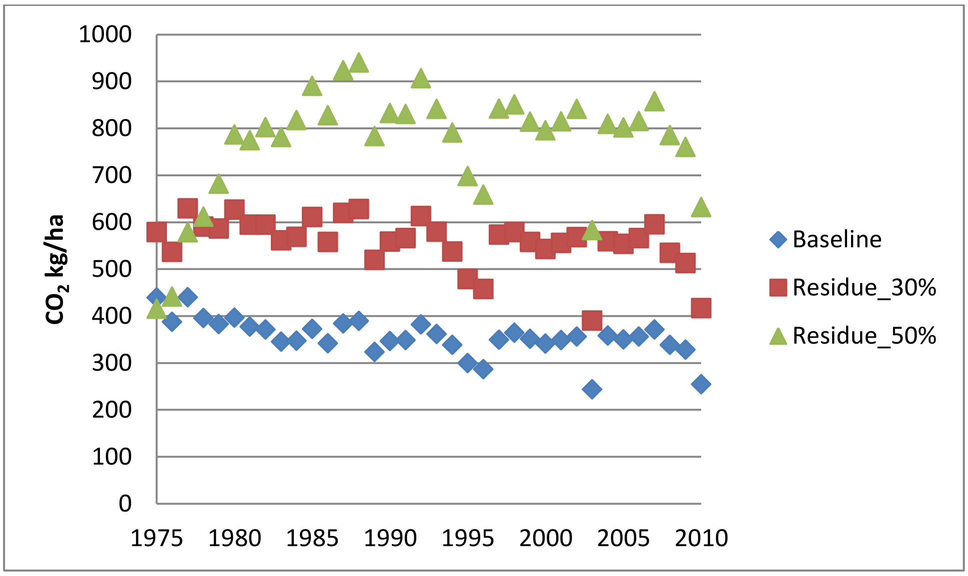


Figure A2.5.6 Modelled CO_2 flux for residue returns of Baseline (15%), 30% and 50% residue returns at 20 g/kg C initial SOC

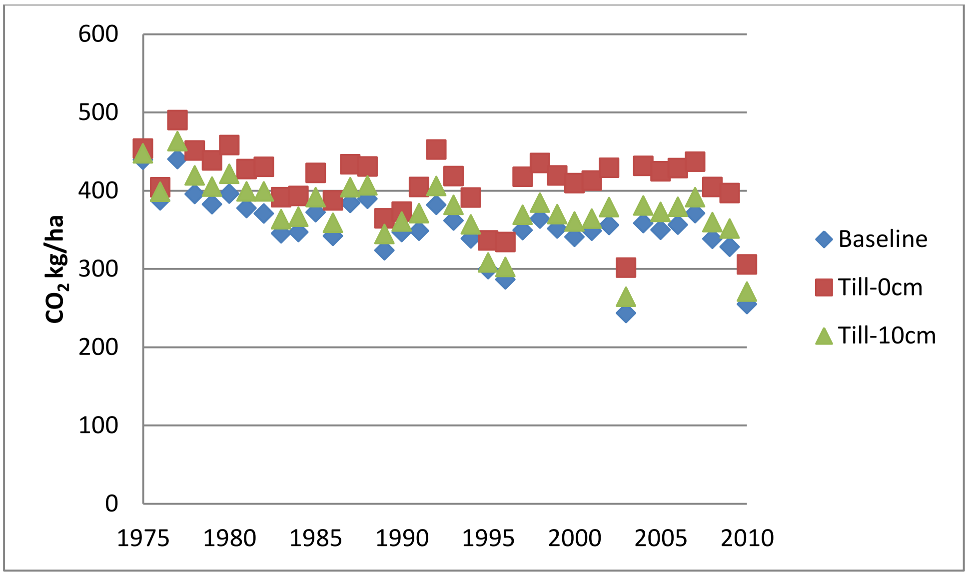


Figure A2.5.7 Modelled CO_2 flux for tillage regime of Baseline, 0 cm and 10cm tillage depth at 20 g/kg C initial SOC

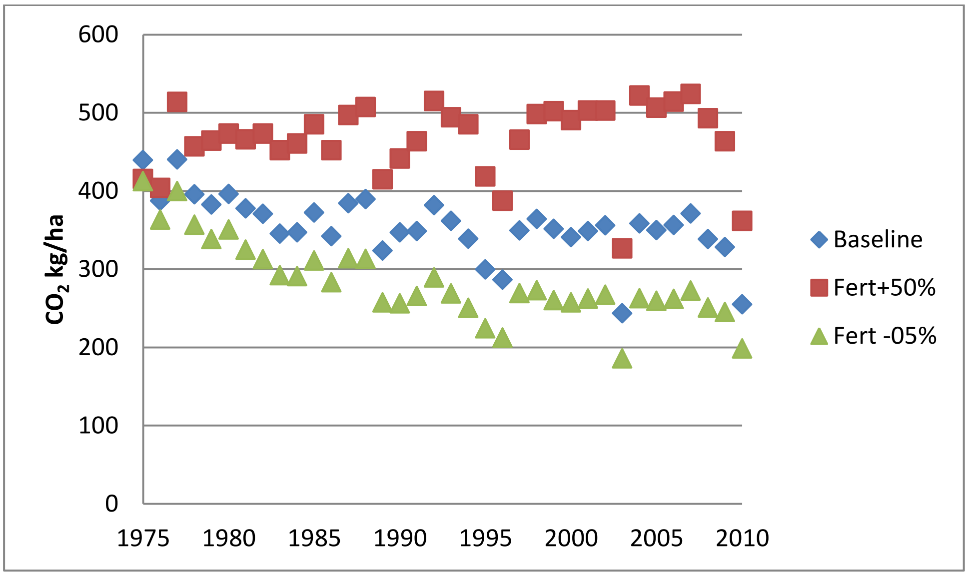


Figure A2.5.8 Modelled CO_2 flux for fertiliser applications of Baseline (210 kg N/ha), +50% additions (315 kg N/ha) and -50% fertiliser application (105 kg N/ha) at 20 g/kg C initial SOC

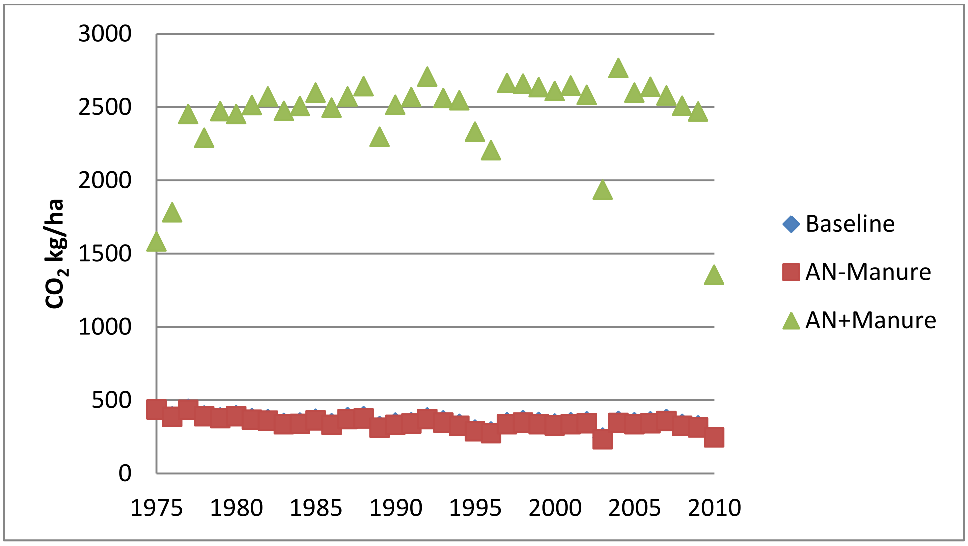


Figure A2.5.9 Modelled CO_2 flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (193 kg N/ha) and AN and manure application at 363 kg N/ha (193 kg AN/ha and 170 kg Manure/ha) at 20 g/kg C initial SOC

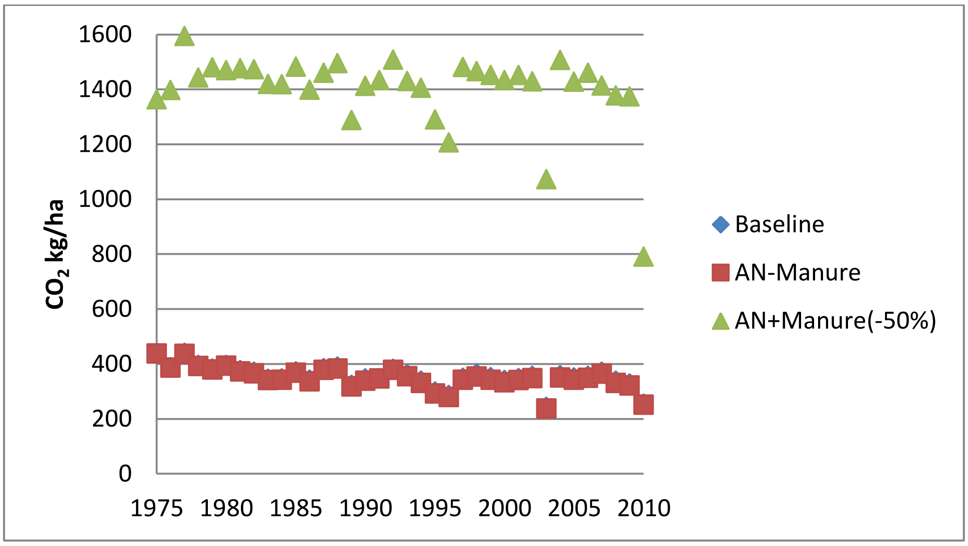


Figure A2.5.10 Modelled CO_2 flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (201 kg N/ha) and AN and manure application at 286 kg N/ha (201 kg AN/ha and 85 kg Manure/ha) at 20 g/kg C initial SOC

Appendix 2.6: Landscape DNDC Scenario Outputs – N_2O Flux

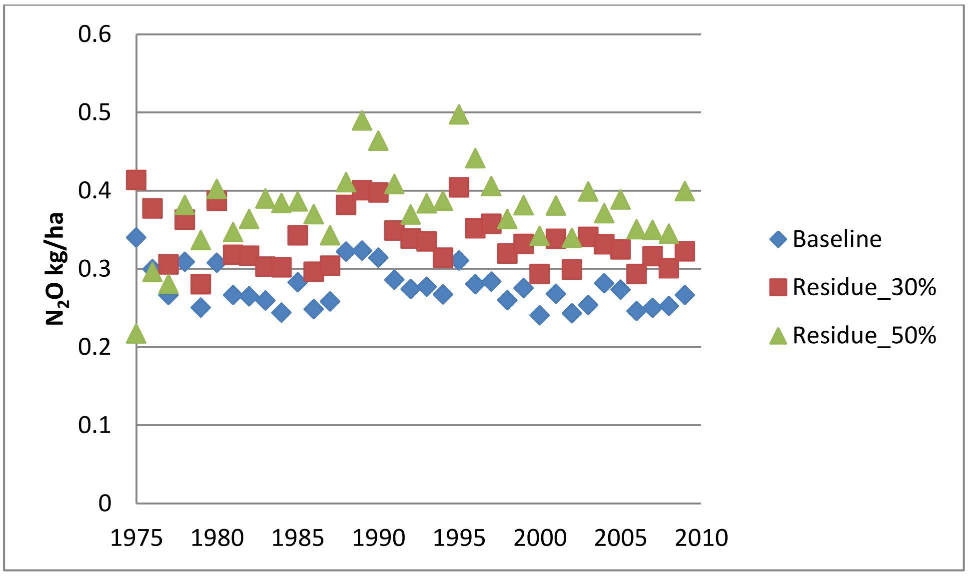


Figure A2.6.1 Modelled N_2O flux for residue returns of Baseline (15%), 30% and 50% residue returns at 10 g/kg C initial SOC

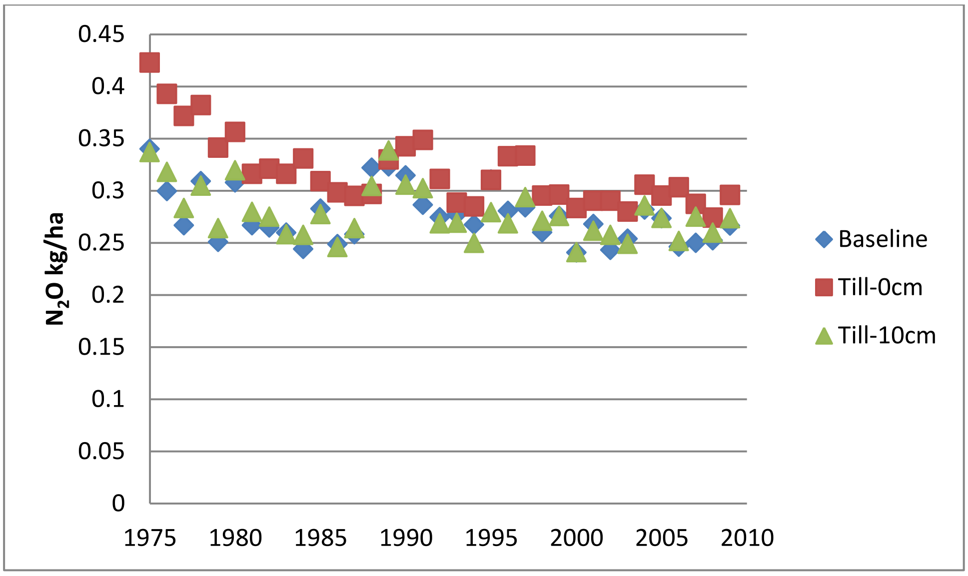


Figure A2.6.2 Modelled N_2O flux for tillage regime of Baseline, 0 cm and 10cm tillage depth at 10 g/kg C initial SOC

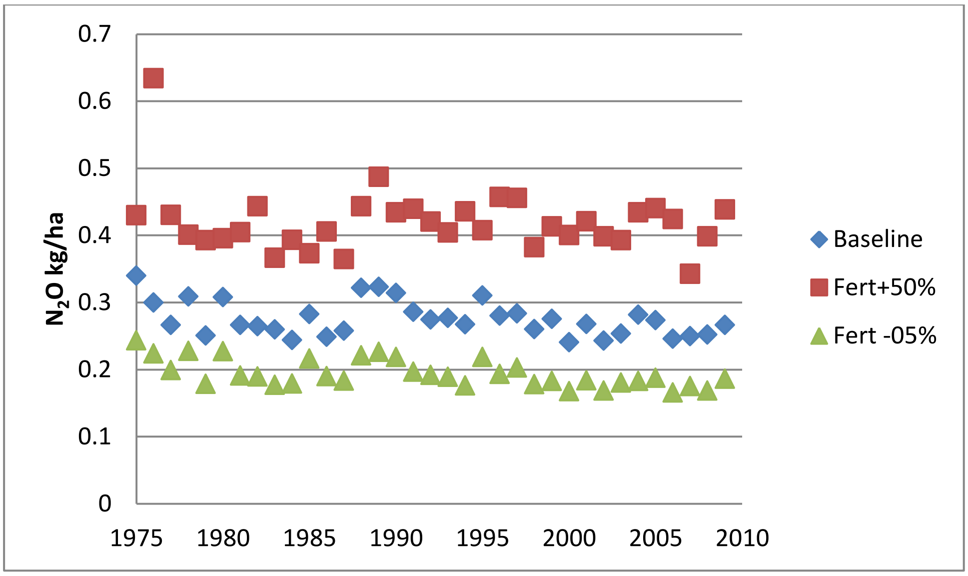


Figure A2.6.3 Modelled N_2O flux for fertiliser applications of Baseline (210 kg N/ha), +50% additions (315 kg N/ha) and -50% fertiliser application (105 kg N/ha) at 10 g/kg C initial SOC

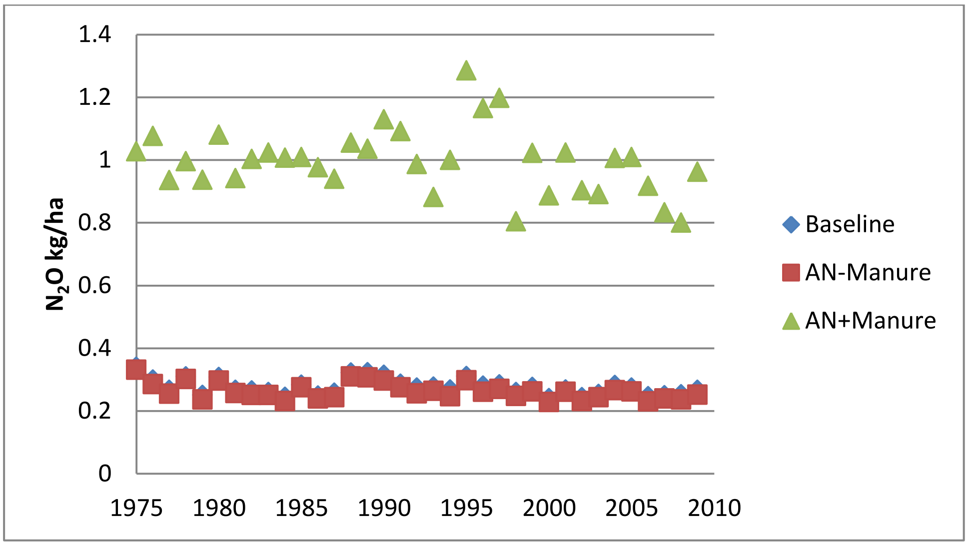


Figure A2.6.4 Modelled N_2O flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (193 kg N/ha) and AN and manure application at 363 kg N/ha (193 kg AN/ha and 170 kg Manure/ha) at 10 g/kg C initial SOC

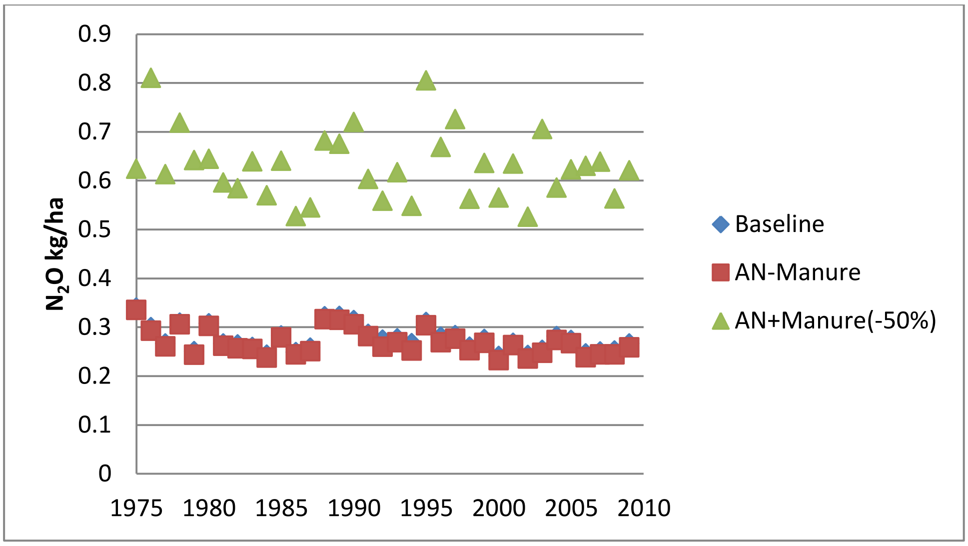


Figure A2.6.5 Modelled N_2O flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (201 kg N/ha) and AN and manure application at 286 kg N/ha (201 kg AN/ha and 85 kg Manure/ha) at 10 g/kg C initial SOC

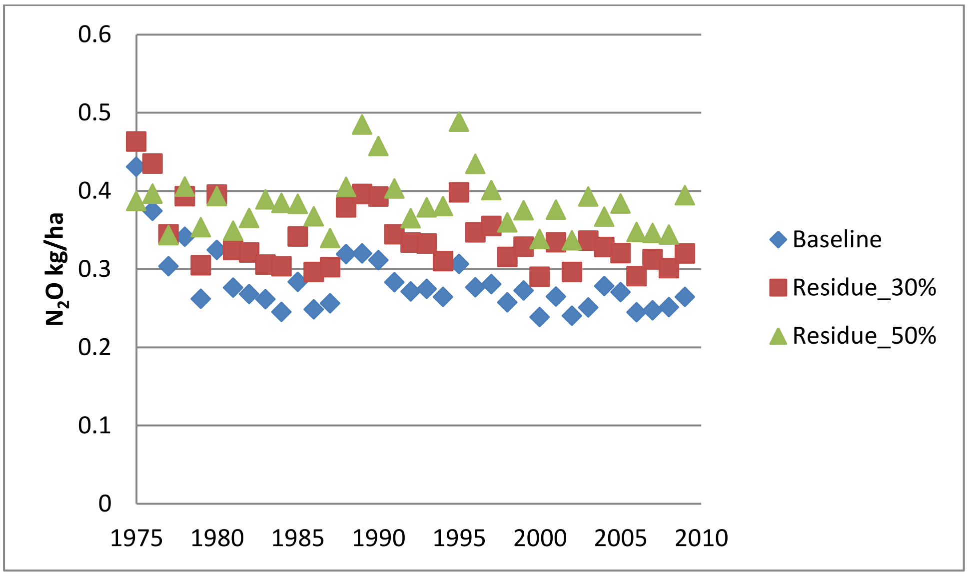


Figure A2.6.6 Modelled N_2O flux for residue returns of Baseline (15%), 30% and 50% residue returns at 20 g/kg C initial SOC

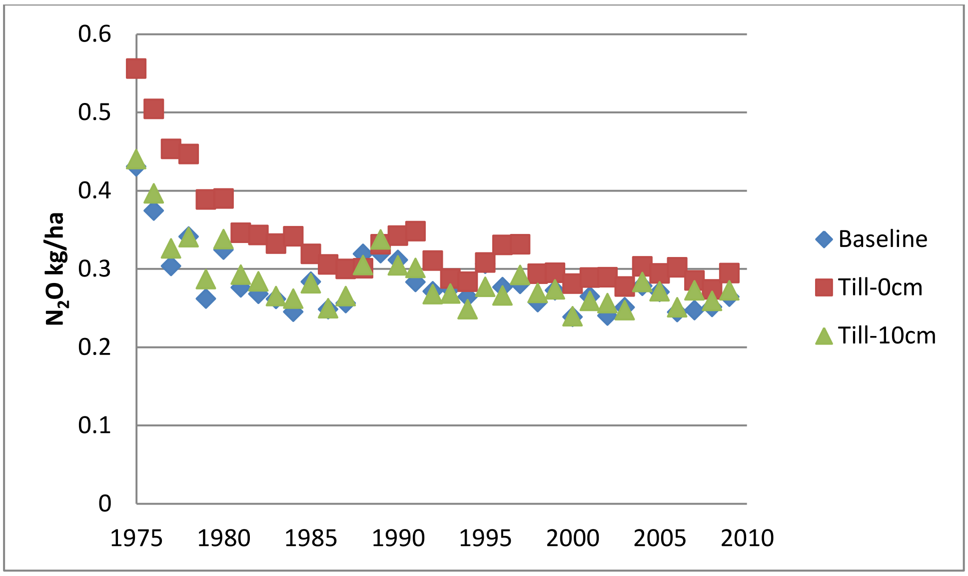


Figure A2.6.7 Modelled N_2O flux for tillage regime of Baseline, 0 cm and 10cm tillage depth at 20 g/kg C initial SOC

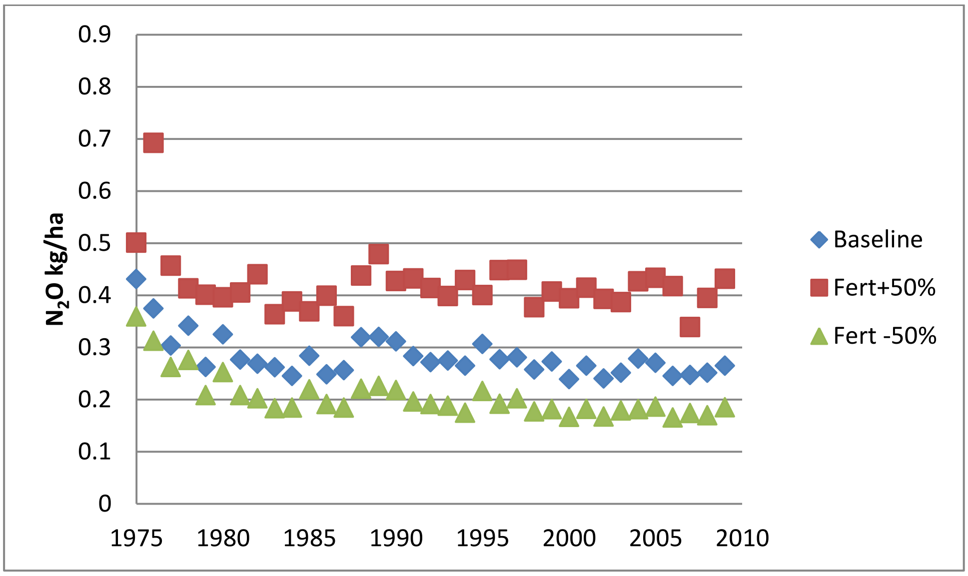


Figure A2.6.8 Modelled N_2O flux for fertiliser applications of Baseline (210 kg N/ha), +50% additions (315 kg N/ha) and -50% fertiliser application (105 kg N/ha) at 20 g/kg C initial SOC

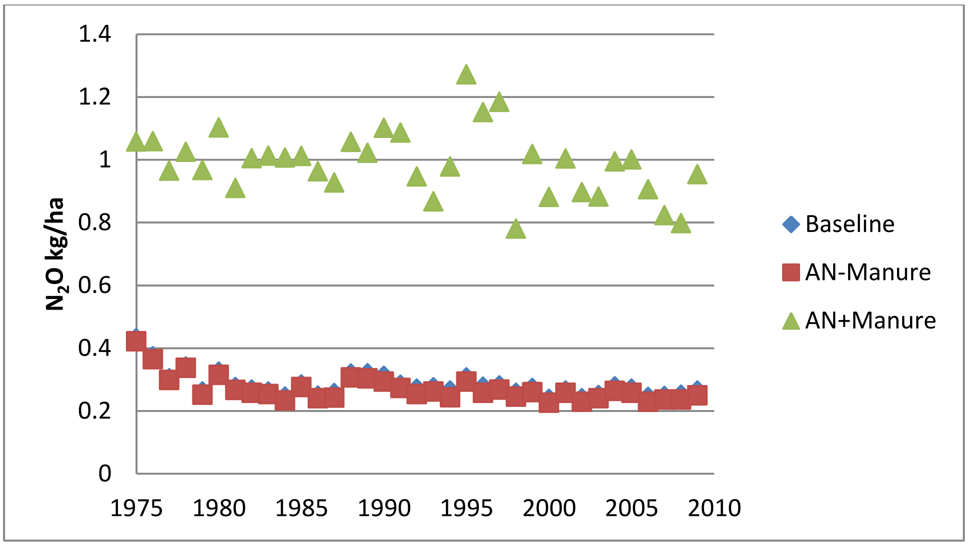


Figure A2.6.9 Modelled N_2O flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (193 kg N/ha) and AN and manure application at 363 kg N/ha (193 kg AN/ha and 170 kg Manure/ha) at 20 g/kg C initial SOC

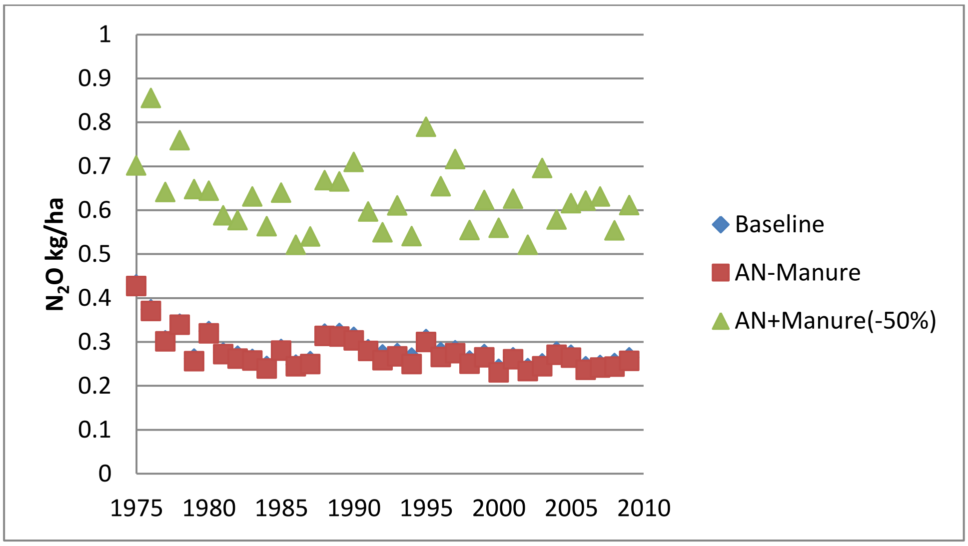
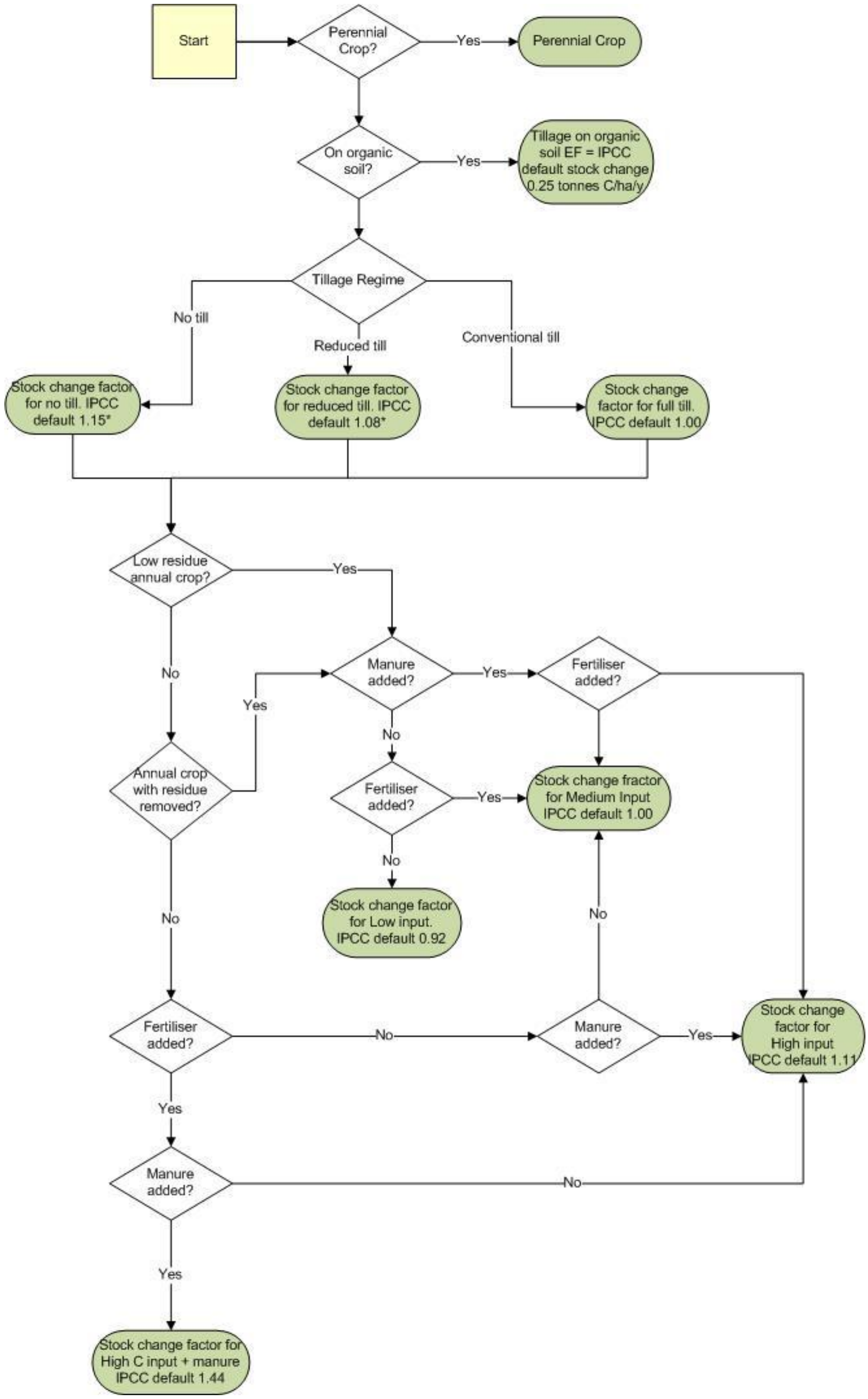


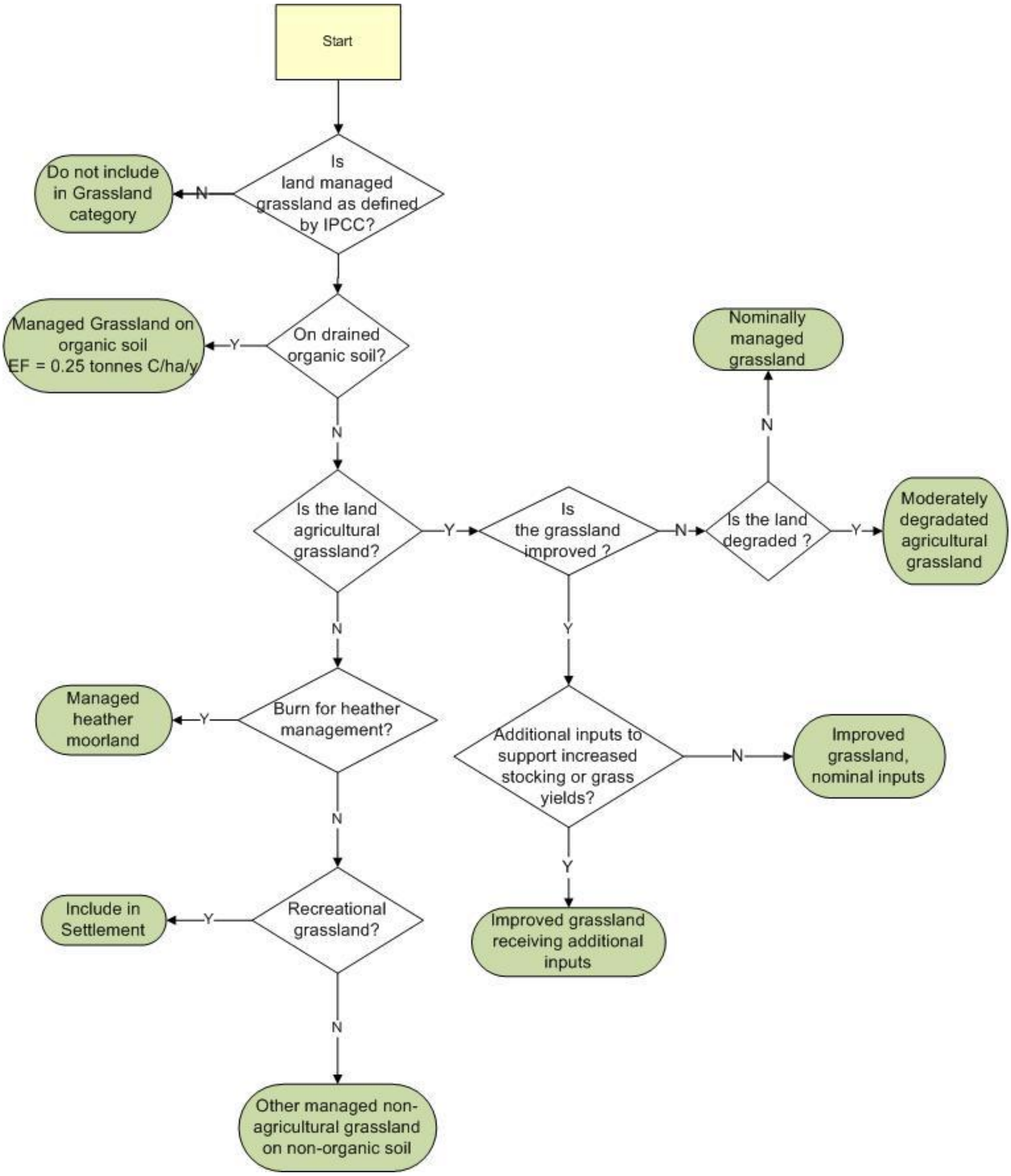
Figure A2.6.10 Modelled N_2O flux for fertiliser treatments of Baseline (210 kg N/ha), AN without manure (201 kg N/ha) and AN and manure application at 286 kg N/ha (201 kg AN/ha and 85 kg Manure/ha) at 20 g/kg C initial SOC

Appendix 3.1 Decision Tree for Cropland Management



*IPCC default stock change factors for tillage regimes are shown for reference. This project found that tillage regime had no effect on SOC stocks under UK conditions and therefore a stock change factor of 1 may be more appropriate.

Appendix 3.2 Decision Tree for Grassland Management



Appendix 3.3 Typical carbon returns from a range of UK arable crops

Crop	Yield[a]	Dry matter[b]	Yield @100% DM[c]	DM Harvest Index[d]	Total above ground dry matter	C returned	Residue class
	t/ha	%	t/ha	All sources		t/ha	
Carrots	45	0.12	5.4	0.6	9.00	1.4	L
Linseed	1.75	0.9	1.6	0.4	3.94	0.9	L
maize	40	0.3	12.0	0.6	20.00	3.2	OTHER
Peas-combining	3.75	0.85	3.2	0.5	6.38	1.3	LOW - N FIXER
Peas-vining	4.75	0.33	1.6	0.34	4.61	1.2	LOW - N FIXER
Potatoes maincrop	45	0.21	9.5	0.7	13.50	1.6	L
Potatoes-early	23	0.21	4.8	0.8	6.04	0.5	L
Rye	6.2	0.85	5.3	0.4	13.18	3.2	OTHER
Spring barley-malting	5.45	0.85	4.6	0.47	9.86	2.1	OTHER
Spring oats	5.5	0.85	4.7	0.4	11.69	2.8	OTHER
Spring oilseed rape	2	0.9	1.8	0.4	4.50	1.1	L
Spring wheat-milling	5.75	0.85	4.9	0.51	9.58	1.9	LOW?
Stubble turnips	35		4	0.6	6.67	1.1	L
Sugar beet	73	0.23	16.8	0.7	23.99	2.9	OTHER
Triticale	5	0.85	4.3	0.4	10.63	2.6	OTHER
Winter barley-feed	6.9	0.85	5.9	0.51	11.50	2.3	OTHER
Winter barley-malting	6	0.85	5.1	0.47	10.85	2.3	OTHER
Winter field beans	4	0.85	3.4	0.5	6.80	1.4	LOW - N FIXER
Winter oats	6.3	0.85	5.4	0.47	11.39	2.4	OTHER
Winter oilseed rape	3.4	0.9	3.1	0.34	9.00	2.4	OTHER
Winter wheat-feed	8.35	0.85	7.1	0.51	13.92	2.7	OTHER

[a]**Yield data .** Yield data for all crops is taken from Nix (2013).

[b]**Dry Matter %** data: All crops except carrots, stubble turnips and maize from a table of data Sylvester-Bradley, R. (1993).

Carrots % DM, from http://cru.cahe.wsu.edu/CEPublications/FS032E/FS032E.pdf

Maize silage % DM from http://www.feedipedia.org/node/12871

[c]**Yield at 100% dry matter:** calculated from yield x DM% except for stubble turnips where yield at 100% dry matter is taken from : http://www.limagrain.co.uk/downloads/StubbleTurnip2011.pdf

[d]**Harvest Indexes**:

OSR: References: OSR HI = 0.34, Berry and Spink (2008);
OSR HI= 0.35, Stoddart and Watts, (2012)

OSR HI = 0.2-0.25 HGCA project report No. 465 (2010)

Cereals: Reference: HGCA (2008) The Wheat Growth Guide. HGCA (2006) The Barley Growth Guide. Also Stoddart and Watts, (2012).

Field Beans. R M Weightman (2005)

Peas: Values taken from ADAS Apt model cross-referenced with R M Weightman. (2005)

Other crops: values from the ADAS Apt model Crop Input table.

[e]Assumes 0.4tC/t dry matter returned (excludes roots)

[f]Assumes <2 t/ha C returned = low residue return (relative to a solid farm manure which returns *c*.3-4 t/ha C)

L indicates Low residues.