Valuing regulating services (climate regulation) from UK terrestrial ecosystems, Report to the Economics Team of the UK National Ecosystem Assessment

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Abstract

This research models physical changes in potential equilibrium carbon stocks from UK agro-ecosystems and woodland and changes in GHG fluxes from UK agricultural activates and agricultural land use change. The analysis is based on the CSERGE land use model run under the high and low UKCIP emissions climate change scenarios from the year 2004 to 2060. As well as modelling the physical changes (through time) in this climate regulating ecosystem service this research also applies marginal abatement costs and social cost of carbon valuations of carbon sequestration/emissions to this ecosystem service. The results suggest considerable changes in the physical provision of climate regulating ecosystem services from UK terrestrial ecosystem over the next 50 years in response to climate change. There is a predicted strong north/south divide, with agricultural GHG emissions per hectare increasing (and terrestrial carbon stocks decreasing) in the north of the UK and decreasing agricultural GHG emissions in the southern parts of the UK. Based on the UK's official non market marginal abatement cost carbon price the cost of GHG emissions from agriculture are predicted to increase from £2.1 Billion per annum in 2004 to approximately £14 billion per annum in 2060 under both the high and low emission UKCIP climate change scenarios.

Introduction

Agriculture accounts for 10-12% of the total global anthropogenic emissions of greenhouse gases (Smith, Martino et al. 2007). Regulation of the carbon cycle and emissions of greenhouse gases (GHG) has therefore become an essential aspect of the agricultural economics in recent years. Including land use choices and land management activities as an integral part of assessments of climate regulation services is important for several reasons. Climate is an important determinant of land use, and climate change would be expected to result in regional shifts in land use. As different land uses are associated with varying regulation capacity, land use change might itself lead to increases/decreases in GHG emissions. Furthermore, land management activities associated with different land uses vary with respect to GHG impact and may offer different potentials for mitigation. Finally, the productivity of land varies across regions; any changes in agricultural production to mitigate climate change impacts would therefore be expected to vary across space. There are therefore multiple ways in which land management, including land use change, impact climate regulation. Assessment of landscape scale changes in climate regulation therefore needs to include the various impacts and assess the relative strength of individual impacts. Modelling the impacts of climate change in agro-ecosystems therefore needs to 1) account for adaptation to climate change through changes in land use, 2) account for the feedback effects due to land use change impacts on climate regulation, and account for the potential variations across space of the magnitude of these two factors.

It is widely accepted that socio-economic factors are important in understanding adaptation to climate change in agricultural systems; nevertheless such factors do not feature strongly in the discussions on impacts of climate change on agricultural production (Yearley, 2009). For example, in the IPCC's report Impact, Adaptation and Vulnerability, the chapter on food and fibre present crop yield-projections based on modelling biological potential (ibid). The results do not include any consideration of how farm decision making might adapt to such changes (2007, Fussel and Klein, 2006). We build on an emerging literature on inclusion of farmer decision-making in climate impact modelling (Fezzi and Bateman, 2010, Seo and Mendelsohn, 2008). This allows us to develop a framework from modelling land-use change and land use change impacts along climatic gradients.

The carbon cycle is impacted both through emissions from agricultural activities and through the changes in stored stocks of carbon. Carbon is stored in live biomass, in soil, in decomposing organic matter, and is exchanged into the atmosphere through respiration and photosynthesis, decomposition and burning of biomass (Erb, 2004). Therefore, any human activity affecting these processes will affect ecosystems' capacity to store carbon. Land management also affect climate regulation through the use of fossil fuel in farm machinery, the use of fertilizers (indirectly as energy is used in their production) and the cultivation or tillage of soils which results in the removal of the topsoil and the break-up of aggregates which tend to capture the carbon in the soil (Pretty and Ball, 2001).

The research presented in this paper was conducted as part of the UK National Ecosystem Assessment. The paper quantifies the changes to the value of climate regulating services (carbon fluxes from above and below ground biomass and soil organic carbon and agricultural activities) provided by UK land based habitats from climate changed induced land use change.

Methods and data

This section outlines the methods used to evaluate climate change impacts on climate regulation and provisioning services in UK agro-ecosystems. We first introduce the framework of analysis, including definition of the system boundaries, the land use change model and the assumptions made in the estimation of the resulting GHG emissions.

Framework of analysis and system boundaries

The analyses are based on the observed or modelled land use share (percentage of landscape) within individual 2km grid squares across the United Kingdom. The carbon stock analysis encompasses both enclosed farmland habitats (EFH) and woodland; while the GHG flux analysis is based on EFH land only (see below for details). The changes in land uses are drawn from the outputs of the CSERGE agricultural land use model (Fezzi and Bateman, 2010) based on the predicted climate change associated with the UKCIP low and high GHG emission scenarios (UKCIP, 2009) for the years 2004, 2020, 2040 and 2060. The farmland—including rough grazing areas—and woodland areas considered for this analysis cover approximately 21.3 million hectares, accounting for approximately 88% of the UK terrestrial area. A further 9% of the UK terrestrial area is under urban development providing little in the way of carbon sequestration, with the remainder 3% being largely coastal extents. As such this analysis, while not being comprehensive does cover the majority of UK land and the most important habitats in terms of climate regulation.

The analysis includes estimates of both the changes in potential equilibrium carbon stocks and the changes in annual flow (fluxes) of GHGs associated with the shifts in modelled agricultural land use. The stock estimates for the model are based on 1) the carbon stored in above and below ground vegetation and 2) the potential equilibrium soil organic carbon (SOC) levels of the soils under those land use patterns. The GHG flux estimates are based on the annual GHG emissions from farm activities (including energy usage, emissions from fertilizers and livestock etc) and the annual SOC emissions or accumulations resulting from changes in land use. All impacts are converted to CO_2 equivalents (CO_2e). We provide an economic valuation of the changes in climate regulation given specified climate change scenarios using the two main approaches to carbon pricing.

The greenhouse gases (GHG) included in the analysis were carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Methane is produced by decay of organic materials in anaerobic conditions. The fermentative digestion in ruminant livestock, stored manures and biomass burning are some of the practices which result in the production of methane (Mosier et al., 1998). Nitrous oxide (N_2O) is released by the microbial action on nitrogen in the soils, manures and from the application of artificial fertilizers (Smith et al., 2007). The emission of CO_2 occurs from burning of fossil fuels, product manufacture (fertilizers, pesticides), packaging of products, transport of products, use of machinery for spraying, spreading, ploughing, drilling, manufacture of machinery etc (Lal, 2004).

Figure 1 gives an overview of the components and activities included in the analysis. Land use shares (i), for each land were modelled, in each 2 km grid across the UK. Livestock$_j$ denotes the distribution of sheep, beef and dairy cattle which is interlinked with land use through the CSERGE land use model (see below). SOC$_{ik}$ denotes the soil organic carbon which depends on land use, $_i$ and soil type, *k*. Soil types (*k*) were defined as either organic (peat) or non organic (non peat) soil types. This distinction was considered important as peat soils have the potential to store considerably greater amounts of carbon that non organic soils and can release large quantities of carbon due to land use changes. $BIOC_i$ describes the above and below ground biomass carbon stock, which is assumed to depend on land use only. Each land use is associated with farm management activities, such as tilling, spraying etc. The carbon emissions based on these activities are included in the model and changes in farm management activities as a result of land use changes are therefore also captured. The other main GHG contributor from agricultural activities is application of fertilisers. Livestock contribute to GHG emissions through manure, releasing N_2O due to excretion of nitrogen in faeces and urine, and CH_4 mainly from enteric fermentation[1]. The analysis does not include introduction of new crops and technological innovation in carbon efficiency.

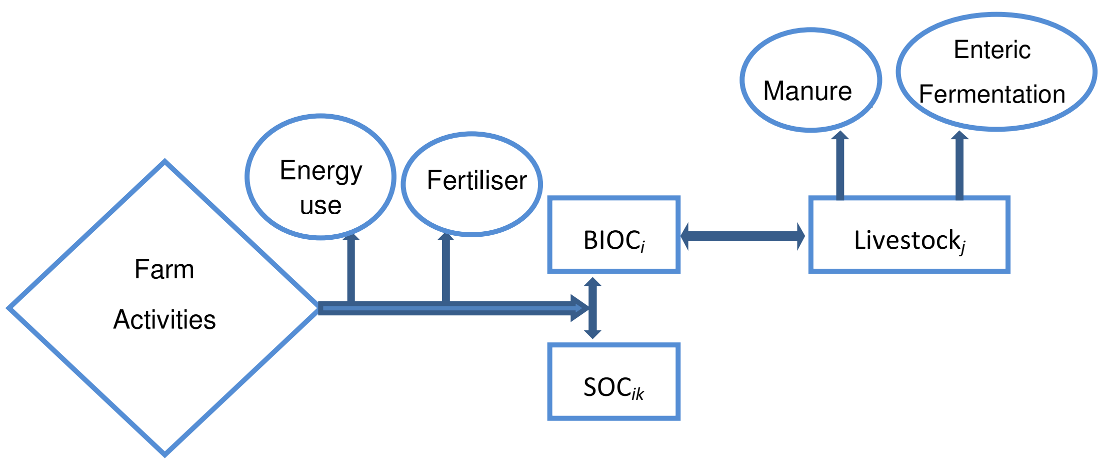

Figure 1 Change in GHG emissions in relation to land use change and associated changes in land management included in the analysis.

[1] Enteric fermentation is a digestive process in which the carbohydrates are broken down by micro-organisms into simple molecules.

Land use change model

We apply the CSERGE agricultural land use model (Fezzi and Bateman, 2010) to model land use change across the climatic gradients of the UK and across selected climate change scenarios. The model is based on the methodology developed by Chambers and Just (1989). This is used to link profit maximisation behaviour by farmers to their consequent land use. The model considers the full range of crops which UK farmers have produced since the 1960s, their livestock, the prices of the harvest, cost of inputs and the existing policy regime including incentives, disincentives and constraints. The model also incorporates detailed descriptions of the physical environmental characteristics of the farm (for more information about the model see Fezzi and Bateman (2010)). Data used for model estimation were collected on a 2km grid square (400ha) basis, the data cover the entirety of England, Wales and Scotland and encompass, for the past 40 years: (a) the share of each land use and the numbers of livestock, (b) environmental and climatic characteristics, (c) policy and other drivers. The original model includes seven land uses, *i* (Figure 1); cereals, oilseed rape, root crops (sugar beet and potatoes), temporary grassland, permanent grassland, rough grazing, and other agricultural land-use (includes, horticulture, on farm woodland and bare/fellow land). Because of the importance of woodland in regulating climate, on farm woodland was disaggregated from the “other agriculture” category in the CSERGE model by overlaying the LCM2000 land cover map (CEH, 2000) with the CSERGE model, creating two additional land use categories “woodland in enclosed farmland habitat” (EFH woodland) and “woodland not in enclosed farmland habitat” (non EFH woodland). While these two categories affect the carbon stock estimates they are not included in the CSERGE land use model and we have therefore assumed that their extents remain unchanged within the climate change scenario timelines.

Changes in the UK enclosed farmlands capacity to store carbon

In this analysis the carbon stocks include the carbon stored in soils as soil organic carbon (SOC)—soil stocks—and in the above and below ground biomass—vegetative stocks. Various studies have estimated these stocks across the UK under different land uses (see for example, Bradley et al., 2005, Milne and Brown, 1997). Carbon emissions can be attributed to the increased soil organic matter decomposition rates due to intensification of cultivation and the loss of top soil due to erosion (Dawson and Smith, 2007). Here it is important to note that what we provide are potential long term equilibrium estimates for SOC stocks. In reality SOC levels are dynamic as they are subject to change in carbon inputs and decomposition rate driven by climate and land management. Moreover, changes in management do not lead to instantaneous changes in SOC and it may be many years after a particular change in land use before SOC reaches anything close to a new equilibrium state. As such the estimates presented here do not represent estimates of the SOC stocks at the given date, but rather represent estimates of the likely levels of SOC for the UK under the particular assemblages of land uses derived from the CSERGE models. Nevertheless, the results presented here provide a useful indication of how climate change and farmer's responses to climate change may change the UK's carbon stocks over time.

Soil carbon stocks

The largest terrestrial carbon stock in the UK lies below ground in the soil as SOC (Bradley et al., 2005). The ability for soils to store carbon in this way depends on the type of soils and the land use applied to those soils along with the related climate, hydrology, topography where the soils are situated (Gupta and Rao, 1994). In this analysis the first two of these factors (soil type and land use) were explicitly modelled. Soil types were defined as either organic (peat) or non organic (non peat) soil types. This distinction was considered important as peat soils have the potential to store considerably greater amounts of carbon that non organic soils and can release large quantities of carbon due to land use changes. National (Northern Ireland, Scotland, Wales and England) estimates of SOC for non organic soils used to allow for consideration of the different climatic, hydrological and typological difference between the four nations of the UK. The average SOC values were derived from Bradley's (2005) estimates as: 132.6 tC/ha of England, 187.4 tC/ha for Scotland, 142.3 tC/ha for Wales and 212.2 tC/ha for Northern Ireland. It was assumed that undisturbed UK peat soils—those soils under rough grazing—had an average soil carbon density of 1200 tC/ha (Bateman and Lovett, 2000, Milne et al., 2001).

The influence of land use (through nutrient cycling and soil disturbance) on the two soil types was accounted for by applying land use factors to the national SOC estimates. It was assumed that non organic soils under arable land uses (oilseed rape, cereals, roots crops and EFH other) have 84% of the SOC of the same soils under improved grassland (temporary and permanent grassland) and soils under woodland and rough grazing (semi natural grassland) have 33% more SOC than improved grasslands (Cruickshank et al., 1998). For peat soils estimates for the annual sequestration of carbon under rough grazing vary from 0.18 tC/ha/yr (Turunen et al., 2002) to 0.36 - 0.73 (Worrall et al., 2009). We took the average of 6 estimates found in the literature as 0.3 tC/ha/yr and assumed that SOC in peat under rough grazing would accumulate this quantity of carbon each year from the baseline estimate of 1200 tC/ha until the analysis year. Further sequestration beyond the analysis year was not considered. Peat soils under temporary grass, permanent grass and woodland were assumed to have an average SOC of 580tC/ha (Cruickshank et al., 1998). Peat soils under arable land uses were assumed to have long term equilibrium SOC equal to the average non organic soil SOC of the region within which the soils are located. Areas of peat soils were identified from European Soil Database (Van Liedekerke and Panagos, 2005).

To check the validity of the model assumptions outlined above the estimate of potential equilibrium SOC for the UK for the scenario baseline year (2004) was compared to the most comprehensive estimate of UK SOC provided by Bradley et al (2005). While Bradley et al (2005) estimated the UK SOC stock as 4563 MtC we estimated 4616 MtC (a discrepancy of 1.3%). The largest discrepancy (5.8%) occurred in Scotland, and is likely to be due to the extensive peat soils found in Scotland and the difficulty in accurately estimated SOC in peat soils due to issues surrounding oil depths along with technical factor associated with the measurement of SOC in peat soils (Chapman et al., 2009). Table 1 shows the estimated average equilibrium SOC for each land use; all estimates are based on SOC up to 1m in depth only.

Table 1 Average SOC estimates for different UK soil types and land uses

	Enland		Scotland		Wales		Northern Ireland	
Land uses	non peat (tC/ha)	peat (tC/ha)	non peat (tC/ha)	peat (tC/ha)	non peat (tC/ha)	peat (tC/ha)	non peat (tC/ha)	peat (tC/ha)
Oilseed rape	111	133	157	187	120	142	178	212
Cereals	111	133	157	187	120	142	178	212
Root crops	111	133	157	187	120	142	178	212
EFH_other	111	133	157	187	120	142	178	212
Temporary grass	133	580	187	580	142	580	212	580
Permenant grass	133	580	187	580	142	580	212	580
Rough grazing	176	1200	249	1200	189	1200	282	1200
Woodland	176	580	249	580	189	580	282	580

Vegetative carbon stocks

Table 2 provides the estimates of the vegetative/biomass carbon stocks for the different agricultural land uses considered in this analysis. The estimates are based on both above ground and below ground biomass, with the assumption that annual vegetative carbon stock represents, in effective, a permanent stock while a particular agricultural land use persists. The biomass lost through harvest in one year is assumed to be replaced by new biomass growth in the subsequent year. For the baseline year (2004) it was estimated that the total UK vegetative biomass carbon stocks was 134MtC, of which 77% is stored in woodland. This is in broad agreement with the findings of Milne et al (2001) who estimated vegetative carbon stocks of 113.8 ±25.6 MtC for Great Britain (England Wales and Scotland only), with 80% is stored in the woodland.

Table 2 Vegetative biomass carbon storage for different land uses

Land use	Carbon stored in vegetation (tC/ha)	sources
Oilseed rape	1.8	(Cruickshank et al., 1998)
Cereals	2.4	(Cruickshank et al., 1998)
Root crops	2.5	(Cruickshank et al., 1998)
Temporary grass*	0.9	(Cruickshank et al., 1998)
Permanent grass*	0.9	(Cruickshank et al., 1998)
Rough grazing (non organic soils)**	1.66	(Milne and Brown, 1997)
Rough grazing (organic soils)**	2.0	(Ostle et al., 2009)
EFH other	1.4	(Cruickshank et al., 1998)
Woodland	36.8	(Milne and Brown, 1997)

* Based on improved grassland category ** Based on semi natural grass category

GHG fluxes from agriculture activities

This section relates to the annual flow of emissions of GHG from farm activities and livestock (Figure 1). Three major sources of GHG emissions were considered in estimating changes in annual GHG emission flows:

(i) The indirect emissions due to energy use from agricultural activities such as tillage, sowing, spraying, harvesting and the production, storage and transport of fertilizers and pesticides. Per hectare estimates of GHG emissions for typical farming practises were applied to each land use in order to map these emissions across the UK.

(ii) Emissions of N_2O and methane from livestock, including beef cattle, dairy cows and sheep through the production of manure and enteric fermentation.

(iii) Direct emissions of N_2O emissions from artificial fertilizers.

In order to estimate GHG emissions from i-iii (above) for the UK it was assumed that agricultural activities can be adequately described from the typical farming practises for each agricultural crop. Aggregate emissions from farm activities are given in Table 3. Further detail on the derivation of CO_2e can be found in appendix 1. Estimated livestock, including beef cattle, dairy cows and sheep, impacts GHG flows through production of manure and enteric fermentation (Figure 1). Manure is distributed to each land use category according to N requirements, details of the calculations can be found in Appendix 1. Enteric fermentation mainly produces methane which we calculate using mean UK emission factors for each livestock and distribute across the UK according to livestock estimates.

Table 3: CO_2e emissions from farm activities related to different agricultural land uses

Land use	Cereals	Oilseed rape	Root crops	Temp grassland	Perm grassland	Rough grazing	others
CO_2 emissions $tCO_2e/ha/yr$	0.55	0.48	0.46	0.48	0.35	0.0	0.40

GHG fluxes from agricultural land use change

This section relates to the annual flow of emissions of GHG from land use change. This comprises of two components: 1) annual SOC fluxes due to EFH land use change. For example, permanent grassland converted from arable farming will be accumulating soil organic carbon (SOC), while permanent grassland on land that was previously under rough grazing may be losing SOC. 2) Annual carbon fluxes from changes in vegetative biomass associated land use changes.

For the Baseline year (2004) annual flows of SOC were only estimated for organic (peat) soils as there is insufficient data on land use change prior to the baseline to accurately model changes in SOC in nonorganic soils. In subsequent analysis years SOC flows from both organic and non organics soils due to land use change were included. Annual SOC fluxes were based on the assumption that organic soils sequester carbon under rough grazing. Estimates for SOC sequestration rates in organic soils vary from 0.18 tC/ha/yr (Turunen et al., 2002) to 0.36 - 0.73 (Worrall et al., 2009). We took the average of 6 estimates found in the literature as 0.3 tC/ha/yr and assumed that SOC in peat under rough grazing would accumulate this quantity of carbon each year. Under arable/horticultural land uses it was assumed that 1.22 tC/ha/yr of SOC would be released from peat soils, and 0.61 tC/ha/yr would be released from peat soil under improved grassland (Eggleston et al., 2006). For non organic soils it was assumed mean equilibrium SOC levels would change from those associated with the previous land uses to the SOC levels associated with the new land uses (see Table 1). SOC accumulation in non organic soils was assumed to occur evenly over a 100 year period, and SOC emissions over a 50 year period (Thomson et al., 2007). For example, a hectare of non organic soil in England converted from cereals to permanent grassland was assumed to accumulate 22 tonnes of SOC before it reached a new soil carbon equilibrium, or 0.22tC/ha/yr over the 100 year accumulation period.

Emissions and accumulations of carbon in terrestrial vegetative biomass were based on the change in vegetative biomass in the move from EFH one land use to another. The change in equilibrium vegetative carbon stock estimate for each 2 km grid (see Table 2) was divided by the time period over which the change occurred to provide an estimate of the annual vegetative GHG fluxes from EFH. Where the modelled annual accumulation of carbon in terrestrial vegetative biomass was lower than in the baseline (within a given 2 km grid square) then there was considered a net emission of GHG. It was assumed that the accumulation and emissions of GHGs associated with unchanged land uses were zero, with annual emissions balancing annual sequestration. Total GHG fluxes from agriculture simply the sum of SOC fluxes, vegetative biomass carbon fluxes and fluxes from agricultural activities within each 2 km grid.

Valuation of climate regulation service and agricultural production

Providing estimates on the price of non-market carbon[2] emissions is problematic, particularly when the estimates are future emissions, for two main reasons. Firstly, climate science is complex and we do not yet have a definitive relation between emissions and climate change. Moreover, there is considerable uncertainty in relations between climate

[2] When talking about greenhouse gas (GHG) emissions the term carbon (or tonnes of carbon) is often used as shorthand for CO_2 or the equivalent of other GHGs (CO_2e) in the atmosphere. For the sake of expediency we will follow this convention here.

change and their impacts on the human economy, dependant as those impacts are on socio-technological responses to changes in the climate. Secondly, when forecasting carbon prices the societal cost associated with the emission of an additional tonne of carbon, or indeed the abatement cost of not emitting that additional tone of carbon, is dependent on how many tonnes of carbon have previously been emitted or abated, the eventual concentrations at which carbon is stabilised in the atmosphere and the emissions trajectory adopted to achieve this stabilisation (DECC, 2009). As such future carbon prices are endogenous to the emission and climate scenarios on which they are based.

The issues of carbon pricing are further complicated by the choice in which non-market carbon prices are constructed. There are two major approaches to carbon pricing, the social cost of carbon (SCC) and the marginal abatement cost of carbon (MACC).

SCC estimates the full effect on social welfare of reducing the emission of carbon by an additional unit (typically a tonne) over the lifetime of that unit of carbon in the atmosphere. As well as based on societal valuation of reducing carbon emissions. SCC provides a theoretical optimal solution in terms of the price (UK) society should be willing to pay now to avoid the future costs resulting from increasing carbon emissions. However, this optimisation approach has been criticised due to the contested basis for monetary valuation of the uncertain climate impacts including the choice of discount rates for future climate change impacts (Downing et al., 2005, Ekins, 2007).

Alternatively MACC is based on the marginal cost of reducing carbon emissions by one tonne. MACC represent the UK government's preferred approach to carbon pricing and the source of official non-market carbon price (DECC, 2009). It has been suggested that advantage of the MACC approach over SCC is that the costs are based on existing activities and technologies, and can therefore be relatively easily estimated empirically (at least in the present time). However, as MACC is projected into the future it becomes increasingly uncertain, as new carbon reducing activities are required to meet emission targets and new technologies alter the abatement costs. Nevertheless, the uncertainty in the empirical estimates of MACC are of two orders of magnitude less than for SCC estimates (Dietz, 2007). As well as a potential empirical advantage the official MACC prices are based on based on judgments of regarding the socially acceptable rise in global temperature and therefore as with SCC approaches, to some extent, take into account the societal value of stabilising atmospheric GHGs.

However, the official UK MACC prices are based on a target constant approach where carbon emissions are assumed to be abated in line with the government's domestic carbon emissions target of at least an 80 percent cut in greenhouse gas emissions by 2050 (Climate Change Act, 2008). As such it is not consistent with either the UKCIP low or high emissions scenarios and cannot be considered an endogenous price. Therefore here we apply two separate prices functions. Firstly, the official central estimate MACC prices from DECC (2009) used here exogenously and applied to both climate scenarios. Secondly we apply an endogenous SCC price from Stern (2007). Stern's business as usual (BAU) price is applied to the UKCIP high emissions scenario and the atmospheric concentration of 550ppm CO_2e price is applied to the UKCIP low emissions scenario. For the DECC prices the carbon price for each point in the scenarios are based on a linear interpolation of the prices provided. Stern's prices are assumed to increase by 2% per year in real terms. Table 4 presents the prices function used in this report. All prices are in 2009 values, calculated using the treasury GDP deflator (HM Treasury, 2010) and Stern's prices were converted from dollars using the long term exchange rate ($/£) of 1.61 Where £/tC were reported a standard conversion ratio of 44/12 was used to convert to CO_2e.

Table 4 carbon pricing for non-market carbon for UKCIP scenarios

YEAR	DECC (£/tCO_2e)	STERN 550 ppm stabilisation (£/tCO_2e)	STERN BAU (£/tCO_2e)
2004	£44.00	£25.47	£88.38
2020	£60.00	£34.96	£121.32
2040	£135.00	£51.95	£180.28
2060	£265.00	£77.20	£267.89

Results

UK Terrestrial Carbon Stocks

Figure 2 shows the potential equilibrium vegetative carbon stock (a), SOC stocks (b) and Total (combined vegetative and SOC) terrestrial carbon stocks (c) for the baseline year (2004). Vegetative carbon stocks are relatively evenly spread across the UK with the highest stocks in forested areas such as Thetford forest and areas of Southern Scotland. SOC is highest in the upland peat areas of northern England, Northern Ireland and Scotland. In the baseline year (2004) 50% of the carbon stocks in the UK terrestrial ecosystems are found in Scotland (2365 MtC), with a further 37% (1755 MtC) in England, 7% (338 MtC) in Wales and 6% (292 MtC) in Northern Ireland.

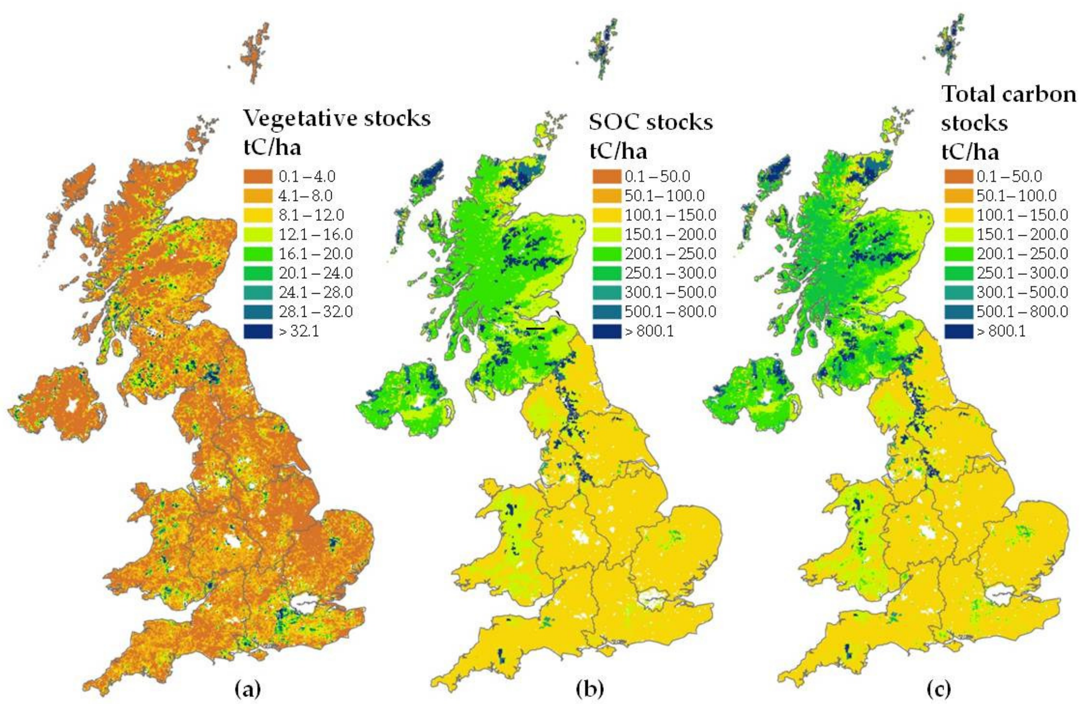

Figure 2 Baseline (2004) potential equilibrium terrestrial carbon stocks for the UK

Figure 3 shows the changes in potential equilibrium carbon stock for the UK due to land use change under the two UKCIP emissions scenarios. With the exception of moderate increases in carbon stocks in Northern Ireland (due to an increased prevalence of rough grazing) only the Fens in the East of England and parts of the North East Scottish Highlands show consistent increase in carbon stocks, again due to a reversion of land use arable farming to rough grazing/semi natural grasslands. The largest reductions in potential carbon stocks occur in peat land and the upland areas of the UK.

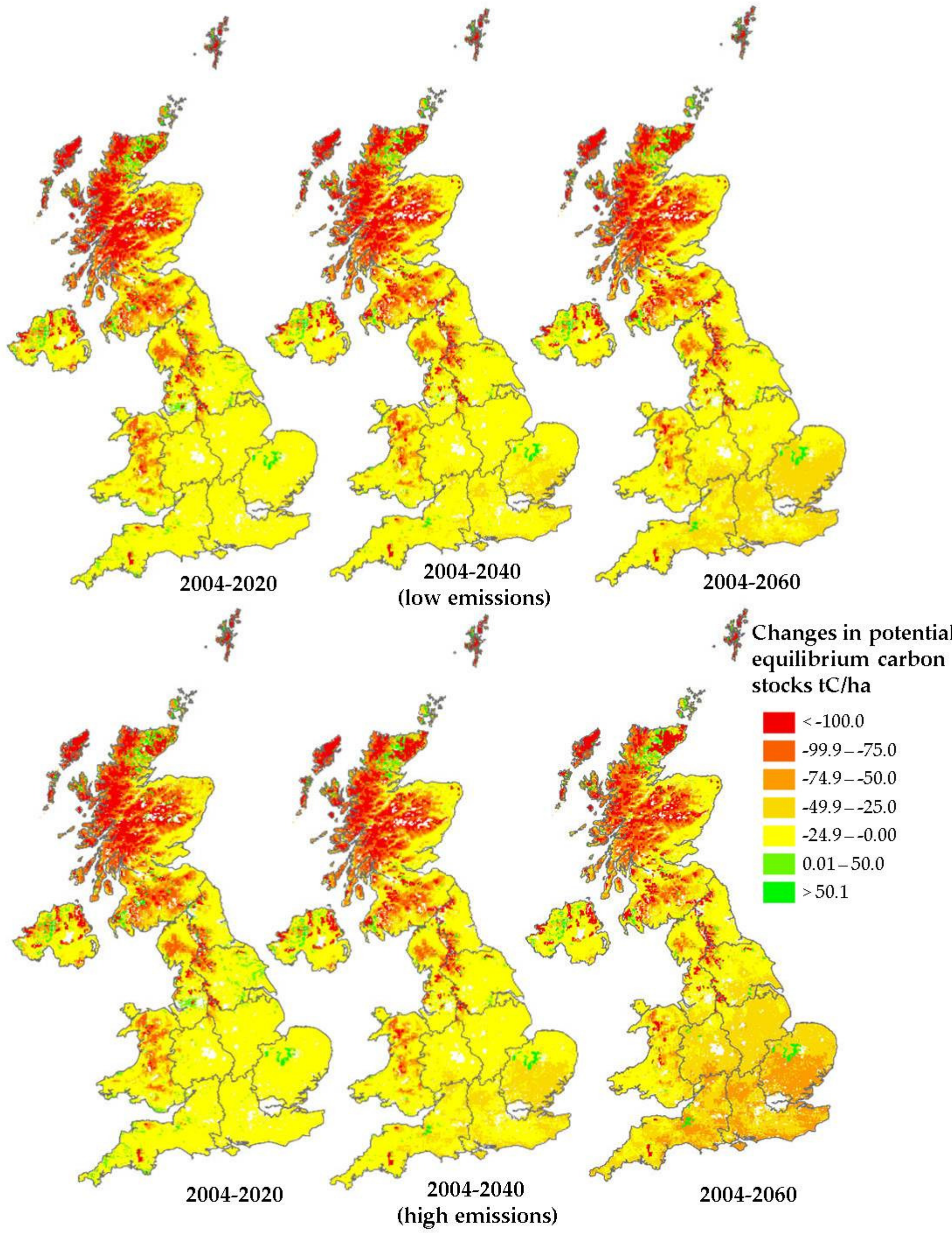

Figure 3 Changes in potential equilibrium carbon stocks for the UK due to land use change under two UKCIP emissions scenarios

Figure 4 shows the regional changes in carbon stocks for the two climate scenarios. The patterns are broadly similar across the two scenarios, although changes in the southern regions increase more rapidly in the high emissions scenario. While there are significant reductions in potential equilibrium carbon stocks in the lowland agricultural regions of Southern England in both the low and high emissions scenarios, the losses are most pronounced in the high emissions scenario for the year 2060.

The total reduction in potential UK equilibrium carbon storage from the baseline year to 2060 is 1381 MtC for the low emissions scenario and 1560 MtC for the high emissions scenario, this would equate to total CO_2 emissions of approximately 5,064 $MtCO_2e$ and 5,719 $MtCO_2e$ respectively. The total UK emissions (excluding embodied emissions from imported goods and services) of GHGs in 2008 has been estimated as 620.5 $MtCO_2e$ (DECC, 2008).

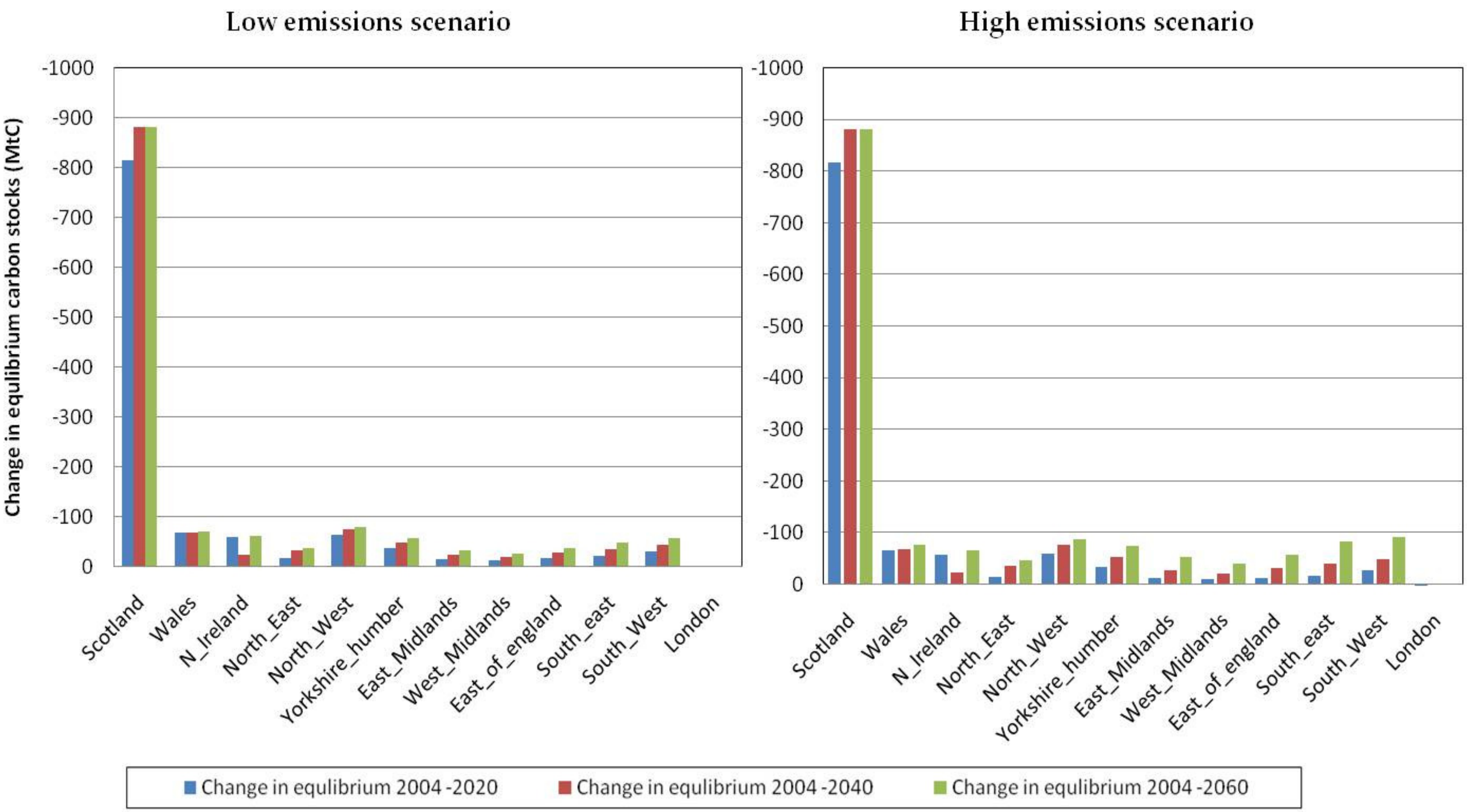

Figure 4 regional changes in potential UK equilibrium carbon stocks due to land use change under two UKCIP climate change scenarios

UK terrestrial GHG fluxes from agriculture

Figure 5 shows (a) the indirect emissions for farming activities including emissions due to the manufacture and application of external inputs, (b) the direct GHG emissions from both artificial fertilizers and manure/slurry from livestock, (c) direct GHG emissions from enteric fermentation in dairy, beef and sheep herds and (d) the total GHG fluxes from agricultural activities.

The annual GHG fluxes from EFH for the baseline year (2004) were estimated to be 35 $MtCO_2e$. Official estimates for the GHG emissions for agriculture for 2004 range from 44.53 $MtCO_2e$ (Thomson et al., 2007) to 51.7 $MtCO_2e$ (DECC, 2008). It is to be expected that our estimate will be below the official estimates as we do not include emissions for pig and poultry farming, or carbon emissions from soils (due to a lack of spatially explicit data on land use change prior to 2004). In the baseline emissions from enteric fermentation and the direct release of N_2O from both artificial fertilisers and the application of manure represented the biggest sources of GHG emissions from agriculture. Emissions were highest in the south of the England, particularly in the South West and lowest in the extensively farmed upland areas of the UK.

Figure 6 shows the changes (from the baseline) in annual GHG fluxes from agriculture activities and agricultural land use change under the two UKCIP climate change scenarios, negative values represent net reductions in annual carbon emissions, while positive values represent next increases in annual GHG emissions for agriculture. In both climate scenarios there are considerable changes in annual carbon emissions. In general the lowland areas of England, showed deceased annual carbon emissions, with the largest reductions in the South West of England.

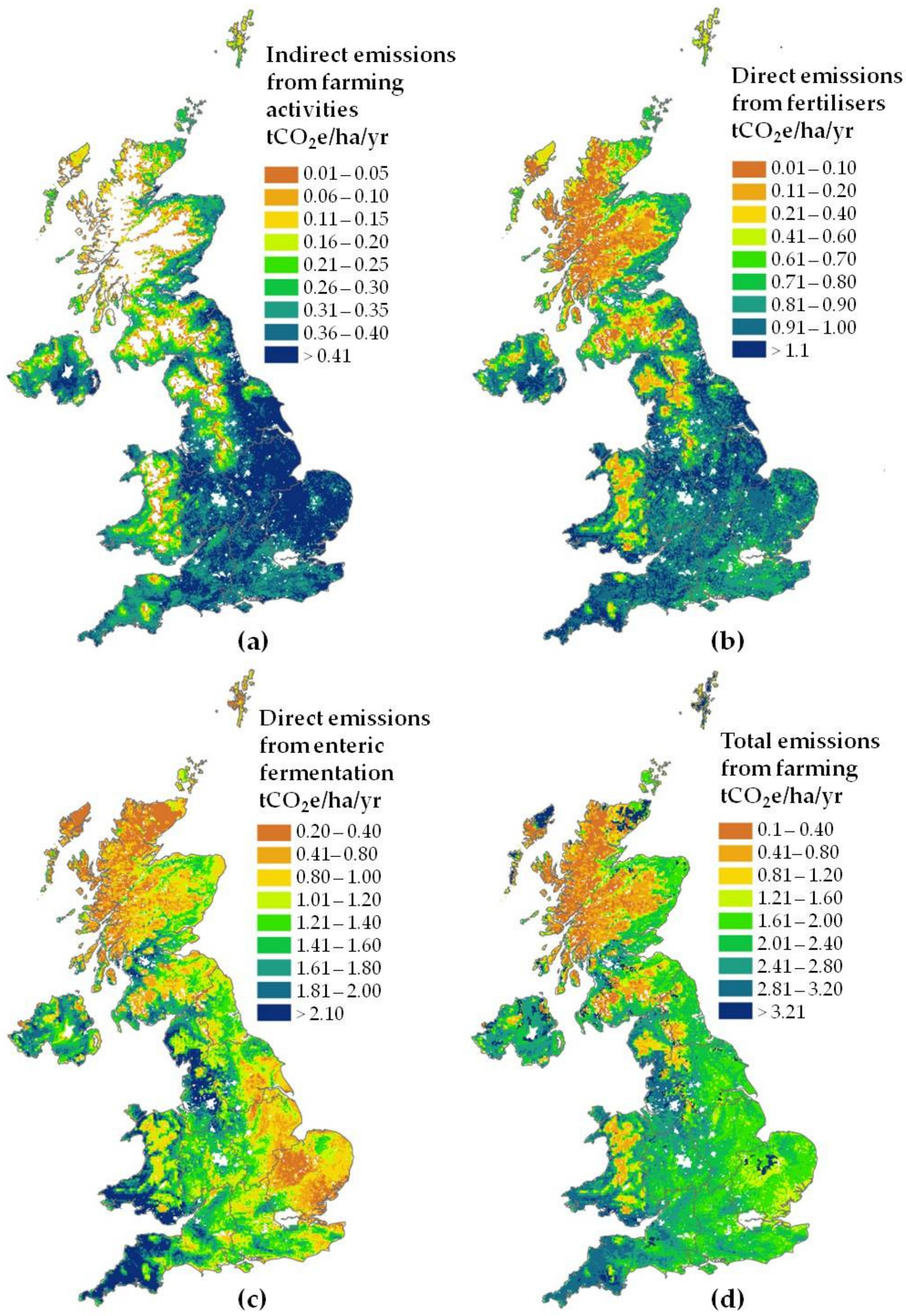

Figure 5 Estimated CO_2e fluxes from agriculture for the year 2004

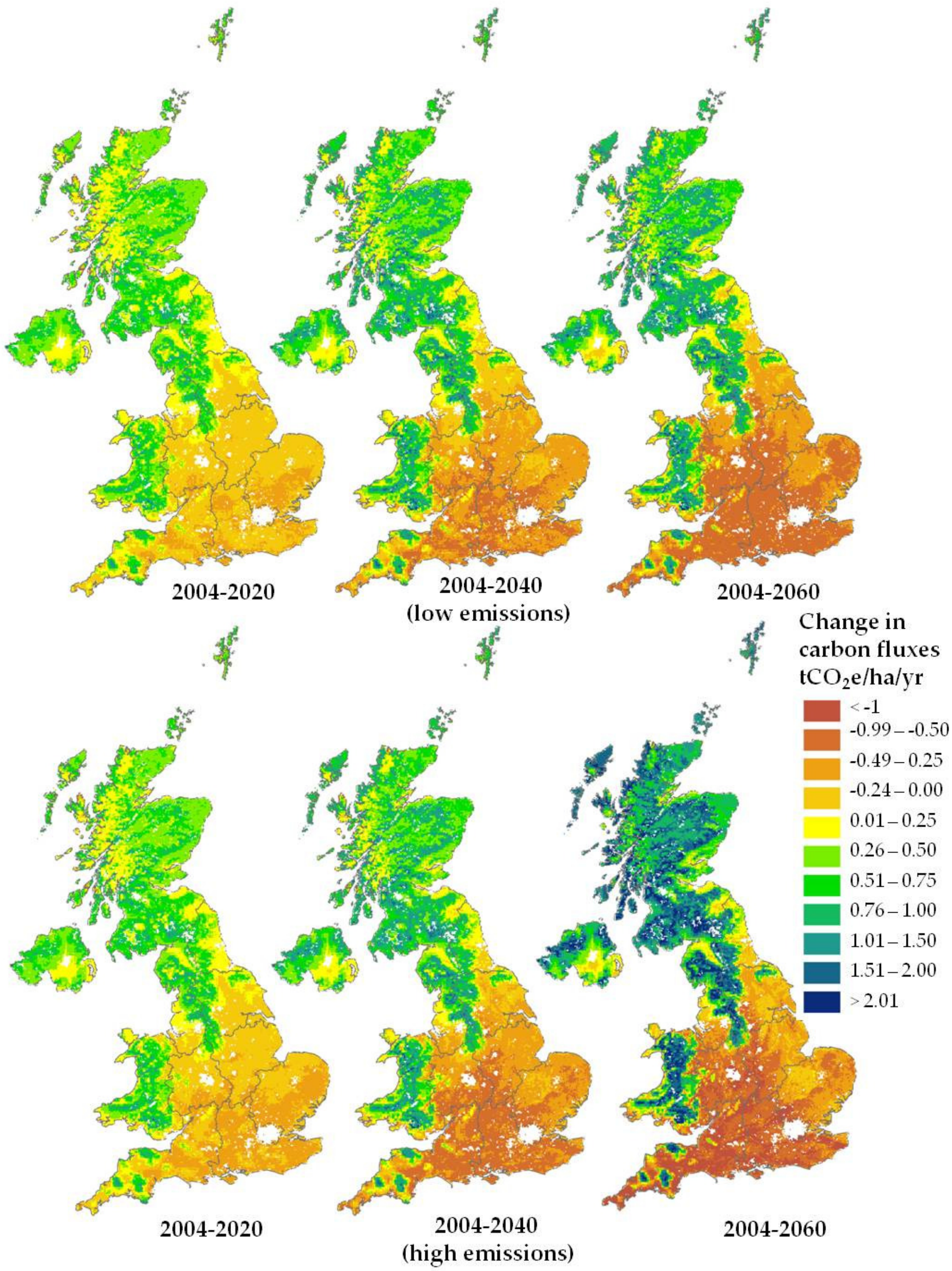

Figure 6 Estimated changes in total CO2e fluxes from EFH land under two UKCIP climate change scenarios

Wales, Northern Ireland, Scotland and the northern upland areas of England are all predicted to show aggregate increase in carbon emissions due to increased livestock numbers and greater presences of arable and horticultural production (as climate change makes these land uses more profitable further north), leading to increase emissions of N_2O and methane. The conversion of peat land from rough grazing/semi natural grassland to improved grassland is also a potentially large source of increased GHG emissions. While the spatial distribution of emissions per hectare are more pronounced in the high emissions climate scenario the overall predicted emissions from agriculture are similar for both scenarios, with UK GHG emissions for EFH estimated as moving from 1.54 tCO_2e/ha/yr to 1.69 tCO_2e/ha/yr in 2060 (UKCIP low emissions scenario) and 1.65 tCO_2e/ha/yr in 2060 (UKCIP high emissions scenario).

The GHG flux models imply an aggregate increase in UK GHG emissions for agriculture of approximately 11% between 2004 and 2020, under both emissions scenarios. Table 5 provides a more detailed analysis of the percentage change in UK annual GHG emissions from EFH. Annual changes carbon fluxes remain relatively stable between 2020 and 2040 for both scenarios (with an approximate change of 11.5% from the baseline year) by 2060 carbon emissions start to decrease with annual carbon emissions 9.7% higher than the baseline for the low emissions scenario and 6.7% lower than the baseline year for the high emissions scenarios. The reduction on GHG fluxes in 2060 (compared to the baseline year) is largely driven by extensification of agriculture in the south of England as the climate becomes less suitable for arable/horticultural farming and a proportion of these land uses are replaced by rough grazing and other grasslands.

Figure 7 shows the regional analysis of changes (from the baseline) in annual carbon fluxes from agriculture. While overall emissions increase, most of this increase comes from the Scotland the North of the England, Wales and Northern Ireland. Scotland is predicted to move from being the lowest emitter of agriculture related GHGs to one of the highest, while Northern Ireland GHG emissions from agriculture are predicted to exceed 3tCO2e/ha/yr under both emissions scenarios by 2020.

Table 5 Changes in annual EFH carbon fluxes from the baseline year for two UKCIP climate change scenarios

	UKCIP low emissions scenario			UKCIP high emissions scenario		
	Change in carbon fluxes 2004 - 2020	Change in carbon fluxes 2004 - 2040	Change in carbon fluxes 2004 - 2060	Change in carbon fluxes 2004 - 2020	Change in carbon fluxes 2004 - 2040	Change in carbon fluxes 2004 - 2060
Scotland	42.4%	56.9%	66.1%	39.8%	60.4%	82.1%
Wales	19.9%	23.0%	22.2%	19.1%	23.4%	18.3%
Northern Ireland	18.7%	21.6%	22.2%	17.8%	23.0%	22.1%
North East	18.7%	20.2%	19.1%	18.0%	21.0%	15.8%
North West	18.1%	21.2%	21.3%	17.3%	21.9%	20.3%
Yorkshire Humber	8.2%	6.0%	2.2%	8.4%	4.8%	-3.8%
East Midlands	-5.2%	-12.8%	-20.3%	-3.6%	-15.7%	-30.1%
West Midlands	-3.6%	-11.7%	-20.4%	-2.3%	-14.6%	-32.4%
East of England	-14.1%	-21.0%	-27.6%	-11.3%	-23.4%	-37.1%
South East	-14.3%	-23.8%	-33.0%	-10.4%	-27.6%	-45.4%
South West	-1.8%	-8.0%	-16.6%	-0.3%	-11.3%	-30.7%
London	-17.4%	-26.7%	-35.5%	-13.2%	-29.6%	-46.4%
UK average	**11.5%**	**11.8%**	**9.7%**	**11.7%**	**11.3%**	**6.7%**

In the baseline year net carbon emissions form UK peat soils is estimated at 3.76 $MtCO_2e/yr$ increasing to 7.67 $MtCO_2e/yr$ by 2060 (high emissions scenario), with Scotland accounting for almost half of these emissions (1.56 and 4.19 $MtCO_2e/yr$ in 2004 and 2060 respectively). These emissions are due to land use change, mainly from rough grazing to more intensive agricultural land uses such as permanent grasslands.

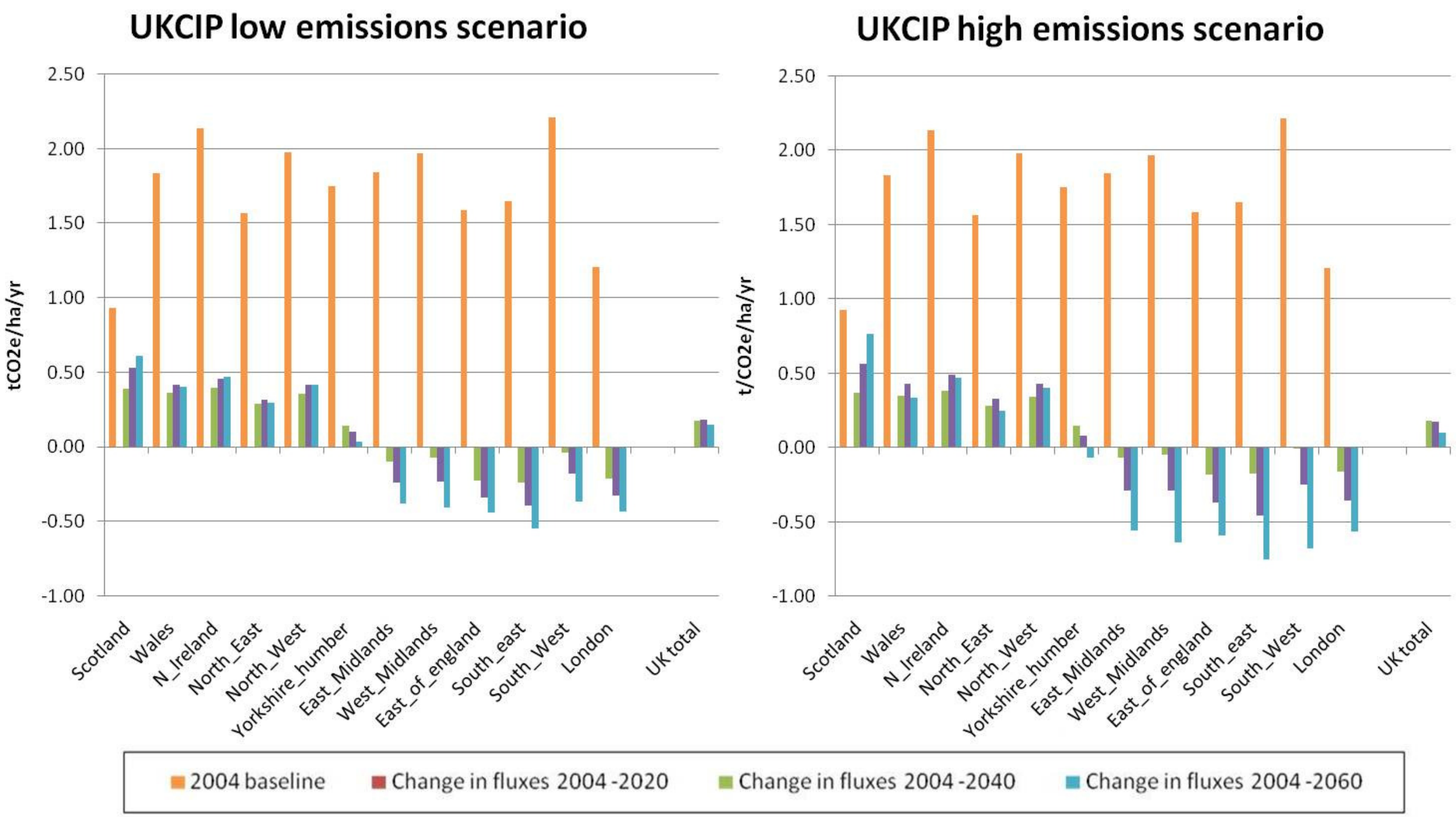
UKCIP low emissions scenario
UKCIP high emissions scenario
tCO2e/ha/yr
t/CO2e/ha/yr
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
Scotland
Wales
N_Ireland
North_East
North_West
Yorkshire_humber
East_Midlands
West_Midlands
East_of_england
South_east
South_West
London
UK total
2004 baseline
Change in fluxes 2004 -2020
Change in fluxes 2004 -2040
Change in fluxes 2004 -2060

Figure 7 Estimated changes (from the baseline) in GHG emissions form UK agriculture from 2004 to 2060 under two climate change scenarios

The value of agricultural climate regulation

The prices provided in Table 4 are used in Table 6 to estimate the total annual cost of GHG emissions from UK agriculture for the predicted land uses under the two UKCIP climate scenarios. The values are based on the modelled changes in GHG fluxes from agriculture presented in the previous section. Annual costs of carbon emissions from agriculture are predicted to increase from £2,134 million per annum in 2004 to £14,000 million in 2060 under the UKCIP low emissions scenario based on the DECC price function and by £4,078 million under Stern's price function. While some of this steep increase in costs is due to the predicted 8.8% increase in GHG emissions from agriculture, it is largely driven by the increase in the predicted price of carbon. To place these costs in context it was estimated that agriculture (including fishing) added a gross value of £64,747 million to the UK economy in 2004 (Office of National Statistics, 2006).

Table 6 Estimated total annual costs of UK agricultural GHG emissions

Carbon price function	2004 (million £)	2020 (million £)	2040 (million £)	2060 (million £)
DECC low emission scenario	£2,134	£3,261	£7,334	£14,000
Stern low emissions scenario	£1,235	£1,900	£2,822	£4,078
DECC high emissions scenario	£2,134	£3,141	£7,121	£13,265
Stern high emissions scenario	£4,286	£6,352	£9,509	£13,409

By calculating the difference between the estimated cost of emissions for the baseline year (2004) and those for the modelled land uses in 2020, 2004 and 2060 we identified the impact of predicted future land use change on the value of carbon regulating service provided UK agriculture. Figure 8 presents a regional analysis of the change in annual carbon costs (per hectare) of climate driven land use change in the UK (for the UKCIP high emissions scenario based on the DECC carbon price function).

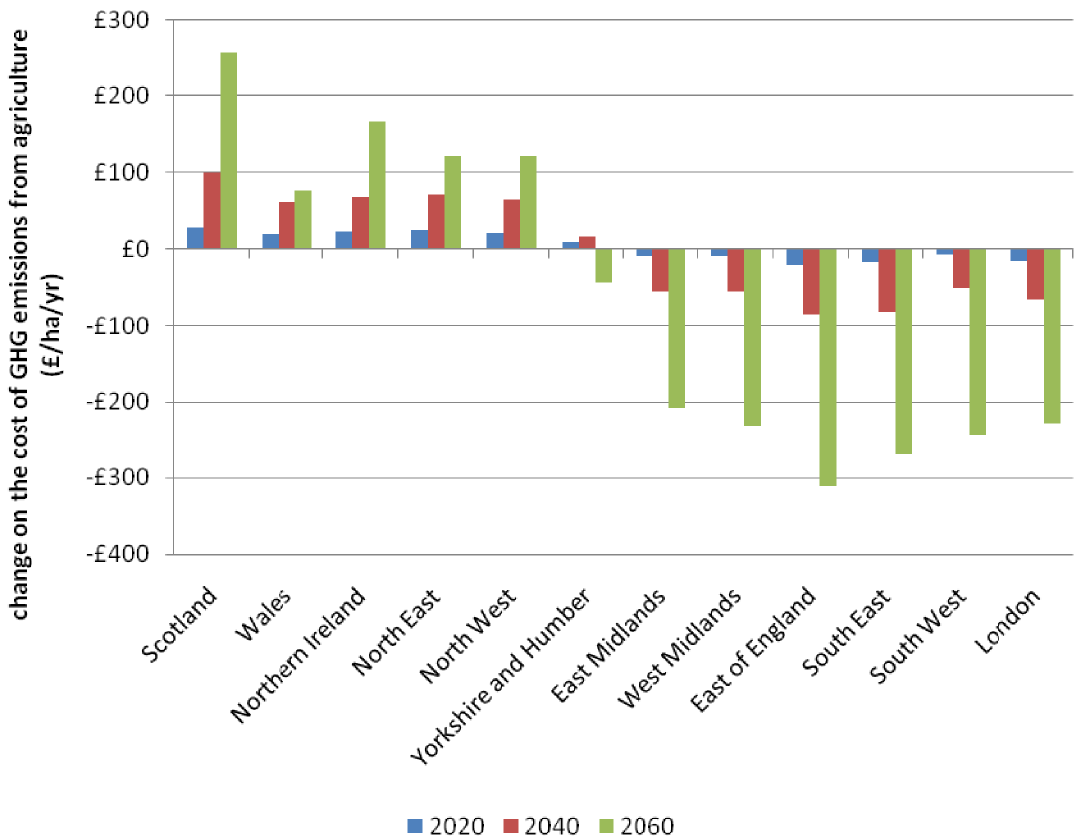

Figure 8 Predicted impact of land use change on the cost of GHG emissions from agriculture in the UK compared to estimated costs in baseline year (2004) For the UKCIP high emissions scenario based on the DECC carbon price function

While agriculture remains a net emitter of GHGs for all regions of the UK, land use changes are predicted to results in decreased costs per hectare of emissions in southern regions of the UK (compared to the cost of emissions associated with the 2004 land uses) and increased costs in northern regions. For example, in 2060 the average cost of GHG emissions from agriculture in the East of England are predicted to more than £300 per hectare lower than would be expected had they maintained the baseline land use patterns, while in Scotland the cost of carbon for agriculture in Scotland is predicted to increase by £250 per hectare due to changing land uses. Table 7 presents a regional analysis of the total cost of annual per hectare emissions of GHG from EFH based on the DECC (2009) MACC price function for the two UKCIP emissions scenarios.

Table 7 Regional analysis of cost from agricultural GHG emissions per hectare (based on DECC prices)

		UKCIP low emissions scenario			UKCIP high emissions scenario		
	baseline 2004 (£/ha/yr)	2020 (£/ha/yr)	2040 (£/ha/yr)	2060 (£/ha/yr)	2020 (£/ha/yr)	2040 (£/ha/yr)	2060 (£/ha/yr)
Scotland	£86	£154	£363	£735	£144	£361	£774
Wales	£89	£155	£355	£660	£142	£335	£615
Northern Ireland	£140	£217	£501	£980	£213	£497	£1,007
North East	£102	£167	£385	£758	£163	£384	£737
North West	£129	£204	£470	£907	£197	£459	£895
Yorkshire Humber	£98	£146	£325	£614	£144	£317	£547
East Midlands	£85	£107	£219	£385	£107	£206	£305
West Midlands	£91	£116	£238	£414	£116	£224	£319
East of England	£90	£101	£203	£356	£101	£191	£233
South East	£74	£80	£158	£261	£83	£144	£175
South West	£108	£143	£302	£523	£139	£279	£404
London	£54	£54	£111	£179	£59	£101	£100
UK total	£94	£144	£324	£618	£139	£314	£585

Table 7 differs from Figure 8 in that it considers the value of a particular set of estimated GHG emissions at a particular point in time[3]. For example, under the high emissions scenario Scotland is predicted to see a nine-fold increase in the cost of agricultural GHG emissions, rising from £86/ha/yr in 2004 to £774/ha/yr in 2060 (Table 7), yet Scottish agricultural GHG emissions are predicted to increase by only around 66% (Table

[3] Whereas Figure 8 identifies the relative carbon costs of changing land uses—the change (from the baseline) in carbon emissions multiplied by the carbon price for a given year (2020, 2040, 2060)—, Table 8 presents absolute costs, in that they are based on the total emissions in a given year multiplied by the price in that year.

5). The majority of the nine-fold increase in absolute carbon costs being driven by a six-fold increase in predicted GHG prices between 2004 and 2060. Using the DECC price function under the high emissions UKCIP scenario the highest cost from carbon in EFH will be in Northern Ireland (£1007/ha/yr) and the lowest (excluding London) will be in the south-east of England (£175/ha/yr). On average the cost of carbon emissions from EFH in the UK is predicted to increase by £491/ha/yr from 2004 to 2060.

Conclusions

This research suggests that agricultural land management responses to climate change over the next 50 years may lead to significant changes in land use and a sharp regional disparity in the changes in GHG emissions for agriculture. The Northern parts of the UK are expected to see decreases in potential carbon stock and increased GHG emission per hectare per year due to increased agricultural intensification as the climate warms. In contrast the Southern parts of the UK are predicted to see increases in equilibrium carbon stocks and decreased annual GHG emissions from agriculture as cereal crops are edged out by rough grazing in a drier wetter future. These changes may have significant impacts on UK attempts to decrease GHG emissions with emissions from agricultural activities and agricultural land use change estimated to increase by around 11% over the next decade.

The spatially heterogeneous land use change and climate regulating ecosystem service responses to the UKCIP climate change scenarios presented in this research, combined with the potentially high costs/values of GHG emissions/sequestration, would the need for greater consideration of the spatial patterns of climate regulation services from UK agro-ecosystems.

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APPENDIX 1: Data used for calculating CO2e for the carbon flow analysis

This appendix includes the information about the data that have been used for calculating the final carbon fluxes from agricultural soils. Here the data will be presented according to the emission types.

CO_2 emissions from farming activities:

Table 1 represents the carbon emissions for each land use specifically for each agricultural activity that is carried out such as tillage, sowing, fertilizers and pesticides (Herbicides, fungicides, insecticides) applications, harvesting and bailing. The estimates have been taken from Lal (2004), which is based on a review of existing studies converted into tCO_2e/ha. The assumptions for the agricultural activities for each land use are based on typical farming practices, which have been taken from the UK agriculture website (UKagriculture.com). The farming practices for each land use type are as follows:

Cereals: A typical production cycle of cereals include onetime conventional tillage (including mouldboard ploughing, two disking, field cultivations & rotary hoeing) emitting 0.13tCO_2e/ha/yr, one time sowing emitting 0.01 tCO_2e/ha/yr, 2 fertilizer sprays emitting 0.24 tCO_2e/ha/yr, 2 pesticides emitting 0.01 tCO_2e/ha/yr (herbicides and insecticides) applications, one time combine harvesting emitting 0.0366 tCO_2e/ha/yr and one bailing emitting 0.12 tCO_2e/ha/yr. **Oilseed rape:** Typical production cycle of oilseed rape includes a conventional tillage 0.13tCO_2e/ha/yr, sowing 0.01 tCO_2e/ha/yr, 3 fertilizer sprays emitting 0.27 tCO_2e/ha/yr, 5 applications of pesticides emitting 0.03 tCO_2e/ha/yr (2 herbicides, 2 insecticides, and 1 fungicide), and combine harvesting emitting 0.0366 tCO_2e/ha/yr. **Root crops:** root crops also involve conventional tillage 0.13tCO_2e/ha/yr, sowing 0.01 tCO_2e/ha/yr, fertilizer spraying 0.26 tCO_2e/ha/yr, 4 pesticide applications 0.02 tCO_2e/ha/yr (including 3 insecticide spraying and 1 herbicide), and harvesting. **Temporary grasslands:** include conventional tillage which is assumed to be occurring only once in four years and emitting 0.03 tCO_2e/ha/yr, sowing also is assumed to be once in four years therefore emitting 0.003 tCO_2e/ha/yr, fertilizer application emitting 0.33 tCO_2e/ha/yr, forage harvesting emitting 0.0011 tCO_2e/ha/yr, and bailing emitting 0.121 tCO_2e/ha/yr. It is assumed that the temporary grasslands are fertilised in accordance with the requirements of dairy farming. **Permanent grasslands:** include only 1 fertilizer application emitting 0.23

$tCO_2e/ha/yr$, forage harvesting emitting 0.0011 $tCO_2e/ha/yr$ and bailing emitting 0.121 $tCO_2e/ha/yr$.

CH_4 emissions from enteric fermentation

CH_4 emissions from livestock are mainly from enteric fermentation (Table 9).

Table 9 Methane emissions from enteric fermentation

Livestock	Emissions from enteric fermentation ($tCH_4/head/yr$)	Total emissions ($tCO_2e/head/yr$)
Dairy	0.1035	2.3805
Beef	0.048	1.104
Sheep	0.008	0.184

Source: (Baggott et al., 2007)

N_2O emissions from livestock manure:

The emissions estimates for fertilizers have been calculated by using the N requirement for each land use category. Cereals (187 Kg N/ha/yr); Oilseed rape (210 Kg N/ha/yr); Root crops (200 Kg N/ha/yr); Temporary Grassland (250 Kg N/ha/yr); Permanent Grassland (175 Kg/ha/yr); Rough Grazing (0 Kg N/ha/yr) multiplying these with the emission values from Lal (2004) to obtain estimates of CO2e. Data on N requirements was used alongside manure excretion estimates from Beaton (2006) to calculate the inorganic fertilizer input requirement given the livestock numbers and land use distribution in each 2 km square across the UK.

In order to calculate how the N_2O emissions are distributed across the land it is necessary to know the time livestock spends grazing and stabled. UK dairy cattle are housed for on average 190 days and grazed for 175 days per year, beef cattle are housed for 151 days and grazed for 214 days and sheep spend 335 days grazing while they are housed for 30 days only during the year (AEA, 2007). It is assumed that the emissions are 100% from farmyard manure when stabled and 100% from deposition on grasslands during grazing periods. The data used to calculate distribution of manure is presented in table 10.

Table 10 Data for emissions from manure supplied by livestock

Livestock	Excretion Kg N/head/yr	Direct application to grasslands		Farmyard manure applications for other land uses	
		Direct application to grasslands Kg N/head/yr	Emissions tCO_2e/head/yr	Farmyard manure applications Kg N/head/yr	Farmyard manure emissions (tCO_2e/head/yr)
Dairy	51.00	24.45	0.1448	26.55	0.0157
Beef	24.80	14.54	0.0861	10.26	0.0061
Sheep	10.00	9.18	0.0543	0.82	0.0005

Sources: (Beaton, 2006, Freibauer, 2003)